INFLUENCE OF CROP-WATER MANAGEMENTS ON YIELD-WATER USE RELATIONSHIPS

By

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To my late father, who never had a chance

to see me grow,

and

to my mother for all the sacrifices,

for her courage and unlimited love

during all these years

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Fresh water resources available for agricultural production are physically limited. This justifies the permanent research aimed at improving on-farm water management for better crop productivity and economic return. The present study was to investigate how to optimize both crop yield and water-use efficiency by coupling irrigation strategies with crop management, and to determine whether intercropping is a more water-use efficient system and achieves better stability of yield than sole cropping.

In two field experiments conducted on a well-drained Millhopper fine sand, corn, sorghum, peanut, and sorghum-peanut intercropped, planted as subplots, were subjected to four water treatments as main plots: optimum irrigation, irrigation allowing two days of wilting on sorghum, or on peanut, and rainfed. Irrigation was scheduled using tensiometers and visible crop water stress symptoms. Water was applied in small amounts to partially replenish the depleted root zone and leave room for any unexpected rainfall. Daily soil water budgets were calculated by the soil water depletion method.

In 1986, sorghum and peanut yields did not respond significantly to irrigation because of fairly well-distributed rainfalls. Conversely, in 1987, yields of corn, sorghum and peanut increased linearly with seasonal irrigation and evapotranspiration (ET). The respective slopes of the irrigation production functions were 511, 204, and 160 kg ha^{-1} cm^{-1} for dry matter, 341, 177, and 67 for grain yields. The corresponding slopes of the ET functions were 627, 486, and 383 for dry matter, 417, 397, and 198 for grain yields. Irrigation-use efficiencies were 82, 45, and 34% for corn, sorghum and peanut, respectively.

Yield levels in the well-irrigated treatments reached their near optimum potentials for all three crops when compared with similar crops grown previously in the region. Based on the land equivalent ratio concept, sorghum-peanut intercrop did not achieve any significant yield advantage over sole cropping in 1986. But in 1987, because of better planting pattern which improved peanut competitiveness, the mixture yielded 15 to 36% more than pure stands, and the yield advantages increased with increasing irrigation. These yield advantages partially or completely disappeared when the analysis was based on the Land Water-Use Equivalency Ratio concept introduced in this study. Similarly, intercropping did not provide any significant water-use efficiency superiority when its conjugate water production functions were compared to those of its equivalent sole crop system. Moreover, intercropping did not achieve a better stability of yield.

CHAPTER 1
GENERAL INTRODUCTION

Food production depends essentially on plant photosynthesis which in turn is controlled by environmental factors such as climate, carbon dioxide, the availability of soil water, and soil nutrients. Crop yield, which is the final photosynthetic output, tends to be proportional to the most limiting of these factors. Achieving optimum yield supposes that the crop is grown under its optimum environment attained through the dynamic balance among solar radiation, temperature, carbon dioxide, soil fertility, and soil water. Usually, the removal of a limiting factor will cause another to become limiting until the limit of the efficiency of solar energy capture is reached.

Crop and soil research has resulted in marked increases in yield of most important crops with proportionate increases in transpiration, thus no change in water-use efficiency. But present yield levels are four to ten times less than the genetic potential as expressed in record yields (Ritchie, 1980; Boyer, 1983). Boyer (1983) stated that these record yields illustrate that the genetic potential for high productivity is already present in the crops of today. As a consequence, even a modest improvement in the ability to realize this potential would boost agricultural productivity in the United States and less-developed countries.

The discrepancy between record and average yields is essentially attributable to biological (diseases, pests and weed competition) and physical (unfavorable soil conditions, unsuitable climate, etc.) factors. According to the USDA (1965), about 15%

of the losses in crop yields in the United States are attributable to biological and about 85% to physical factors. There is hope for increasing food production per unit area of land if the necessary inputs for higher production are available, especially in less-developed countries. Another alternative would be to increase the area of agricultural land. Considering that most of the best land where water is available is already used for food production, Ritchie (1980) stated that there seems to be a greater potential for increasing world food production through improvement in yield than in expansion to new land.

In the developing countries of South America, Southeast Asia and Africa, multiple cropping has been practiced for generations as a way of improving productivity. One such farming system, intercropping, consists in growing two or more crops simultaneously in a sufficiently close intimacy to allow intercrop competition on the same piece of land. This practice is deeply rooted in the socio-cultural and economical environment of farmers in these regions for many reasons: small sizes of farms, low productivity of soils, land shortages, low productivity of labor, unpredictability of rainfall, little control of water resources, low technology and income levels, and limited access to credit...(Steiner, 1984; Willey, 1979). The implementation of this cropping system differs frequently from one area to another; cropping patterns and crop mixtures vary accordingly and can become very complex.

It is only very recently that intercropping has awakened real interest among researchers. There seems to be an increasing evidence that intercropping can provide substantial yield advantages over sole cropping (Andrews and Kassam, 1976; Willey, 1979; Baker, 1978 and 1980). Other suggested advantages of this practice include greater stability of yields over different seasons or environmental conditions, better use

of available resources, less incidence of pests, diseases or weeds, and improved nitrogen economy when a legume is present (Willey, 1979).

In most environments, the major causes of year-to-year variation in crop yields are fluctuations in soil nutrients and in weather. The distribution and amount of precipitation are the components of weather causing the greatest variability. Water resources are physically limited in quantity, quality, occurrence and spatial distribution. In the global hydrological cycle, annual evaporation equals annual precipitation. But at regional and local scales, there can be tremendous imbalances between these two components, giving considerable opportunity for improved water management. According to Hagan (1976), water management in the future will certainly not be the development of new supplies, but a more intensive management of relatively fixed water supplies and possibly a reallocation of existing water resources among competitive uses and users. Agriculture is by far the biggest water consumer. Adequate water supply that would obviate any deleterious crop water stress during the growth cycle is essential to achieving the yield potential of most crops. This sometimes requires supplemental water input by irrigation. Irrigation in humid regions like Florida can be economically justified even though annual precipitation exceeds annual evaporation. Three factors can contribute to this situation:

(i) the lack of coincidence of rainfall and evaporation patterns;

(ii) soils with water holding capacities insufficient to provide adequate water supply to crops during deficit rainfall periods;

(iii) limited depth of root zone in the early stages of plant growth, and later due to natural and man made root-impeding layers.

All three factors can occur separately or in combination at anytime during the growing season, which runs from March to October for field crops in Florida.

The physiological importance of water cannot be over-emphasized. Among other vital functions, water is the cooling material for leaf tissues. Plants absorb from the soil, transport, and lose to the atmosphere quantities of water many times greater than they use in their own metabolic processes. The loss occurs through the stomates on the leaf surface which are normally open during the day to take in carbon dioxide necessary for photosynthesis. The pathways of water vapor and carbon dioxide at the leaf-atmosphere interface are thus quite similar, though in opposite directions. That is why the amount of water consumed by a given crop is expected to be highly correlated to the total dry matter produced by photosynthesis. If the evaporative demand of the atmosphere exceeds the rate of absorption of soil water by the roots, the stomates may close partially or completely to reduce water loss. Photosynthesis will then also be reduced because carbon dioxide entry is limited.

Thornthwaite (1948) defined evapotranspiration (ET) as the combined evaporation from the soil surface and transpiration from plants. The concept of potential evapotranspiration introduced by the same author stems essentially from the fact that under the most favorable growing conditions where the soil surface is completely covered by the crop canopy and soil water is not limiting, climate determines, to a great degree, a plant's need for water. But seldom are these conditions met in most agricultural lands. Usually, water supply is permanently or at least temporarily limited. This results in actual ET rates which are less than potential ET much of the time during the growing season. Tremendous losses in plant growth occur annually because of recurrent and periodic or sustained internal water deficits in

plants. The amounts of such losses are usually unknown because data for many areas are not available to indicate how much more growth would occur if plants had favorable water supplies throughout the growing season. Water production functions (defined as dry matter or marketable yield as a function of seasonal water use), and water-use efficiency (defined as the ratio of crop yield to water use) can provide this kind of valuable information. This requires reliable estimates of the amount of water actually used by the crop.

Transpiration is difficult to measure under field conditions where crop water use is usually expressed in terms of actual evapotranspiration or irrigation water. Methods for ET assessment can be grouped into three categories: water balance methods (including catchment, soil water depletion, and lysimetry), micrometeorological methods (including aerodynamic, energy balance, combination of both, and eddy correlations), and empirical methods (formulas). While the first two categories have a rational basis, empirical methods must be calibrated by relating the predicted ET values to actual ET measurements. The different techniques used in assessing ET were developed in response to various constraints such as the availability of data for estimating ET, the intended use, the temporal and spatial scales, the precision needed, the convenience and cost (Tanner, 1967; Jones et al., 1984). Each method has its advantages and limitations, and none is totally preferred.

The water depletion method is based on the field water balance equation which states that water brought by precipitation (P) or irrigation (I) in a given area during a given time period can be partitioned into storage in the rhizosphere (ΔS), evaporation from soil and plant surfaces (ET), surface runoff (R), and percolation deeper than the root zone (D). The accuracy of this method for measuring ET depends largely on how

well the other components of the equation are evaluated. Measurements of P, I and ΔS are relatively easy. In certain conditions (level, well-drained, coarse-textured, and deep soils), R can be assumed negligible. The most difficult parameters to measure are ET and D. The main problem comes from the uncertainty in partitioning the soil water depletion between root uptake (ET) and deep drainage. Any scientifically sound method for such partitioning requires that at least one of the two components be determined or predicted independently. Many approaches have been used for the assessment of D (Rose and Stern, 1967; Larue et al., 1968; van Bavel et al, 1968a and 1968b; Cary, 1968; Black et al., 1969; Nimah and Hanks, 1973a and 1973b; Miller and Aarstad, 1972; Hillel et al., 1975; Rao et al., 1976). The instantaneous profile (or internal drainage) method has been used successfully by many investigators (Hillel, 1972) for in situ hydrodynamic characterization of soils. This method can be appropriate for the prediction of drainage in a field prior to the establishment of a crop.

While the transpiration water-use efficiency has been shown to remain relatively constant for a given crop in a given environment (Tanner and Sinclair, 1983), Viets (1962 and 1966) suggested that there were considerable opportunities to increase the ET efficiency in field-grown crops. One strategy is to maximize the transpirational use of available water resources while minimizing the amount of water lost by direct evaporation from bare soil, surface runoff, and deep percolation beyond the root zone (Hammond et al., 1981a; Tanner and Sinclair, 1983). Besides the achievement of an increased yield per unit of water evapotranspired (better water-use efficiency), this practice can result in other practical advantages:

(i) - better fertilizer and pesticide economy by reduced leaching and runoff;

(ii) - better soil conservation by reduced soil erosion;

(iii) - reduced pollution of the groundwater by the agrochemicals.

In practice, improved water-use efficiency may be achieved by a better control of water resources through irrigation scheduling, improved soil and fertilizer management, and better cropping systems to maximize yields. Since WUE is a ratio of yield (dry matter or marketable product) over water use (ET or irrigation) it can be improved by increasing the numerator (yield) or by decreasing the denominator (water use), or both.

It has been reported that yield advantages of the sorghum-peanut intercrop over sole cropping were greater under droughty than under well-watered conditions, thereby suggesting that the observed advantages come about through the combination of temporal and spatial complementarities of the two component crops (Natarajan and Willey, 1986; Harris et al., 1987). In other words, the mixture would use water more efficiently both in time and in space as compared to sole cropping. This viewpoint is not shared by Trenbath (1974) and Loomis (1983), who suggested that intercropping would in fact be less water-use efficient and would seldom outyield the best monocropping. Plant species, instead of being complementary in their use of available resources as reported by Natarajan and Willey (1986), actually compete for the same basic elements (light, CO_2, soil water and soil nutrients). Mixed cropping is practiced in primitive systems where soil nutrients are strongly limiting. In such conditions, plant growth is generally poor and there is little competition for light. This would implicitly imply that the reported yield advantages may result from a poor management of sole cropping rather than a better or more efficient use of available resources by intercrop systems. In order to assess any advantage, it is therefore critical that both cropping systems be grown under their respective optimum agronomic and environmental conditions. The apparent conflicting biological efficiency of

intercropping may also be due to the conceptual basis on which the sole cropping versus intercropping comparisons are conventionally made (Hiebsch and McCollum, 1987). Furthermore, it has been suggested that intercropping may provide better stability of yield over different environments or seasons, thereby reducing the risk of failure (Willey, 1979), but this claim is yet to be documented.

The main objective of the present study was to investigate how field water-use efficiency can be maximized, or rather optimized by coupling water management with two different cropping systems: sole cropping and intercropping. More specifically, the objectives were

(1) to use the instantaneous profile method of determining unsaturated hydraulic conductivity of the soil in order to predict deep drainage of water below the rhizosphere in a corn, peanut and sorghum fields;

(2) to measure daily ET using the soil water depletion method in order to evaluate the differential water uptake patterns of these three crops grown separately or in association;

(3) to derive water production functions for the respective crops and cropping systems and test the hypothesis that intercropping is a more water-use efficient system than sole cropping;

(4) finally, to investigate the assumption that intercropping achieves better stability of yield across a variety of crop water stress conditions, as compared to sole cropping.

CHAPTER 2
HYDRODYNAMIC CHARACTERIZATION OF THE SOIL IN THE EXPERIMENTAL SITE

Introduction and Literature Review

The ranges of soil water status over which most crops achieve highest yields are fairly well known and documented. But it is difficult to maintain a soil at a specified water content over a period of time. Well-drained sandy soils have high infiltration capabilities allowing for quick intake of rainfall or irrigation water, good aeration characteristics which favor root development, and self-mulching properties which reduce the loss of water by evaporation. Their major physical deficiency is the low capacity for retaining water, requiring frequent rains or irrigation to keep the water content at a level which prevents plant water stress.

A major problem encountered in the effort to increase field water-use efficiency in sandy soils is the difficulty of controlling the amount of drainage out of the root zone. One strategy would be to balance the frequency and quantity of irrigation against the evapotranspirational demand and the leaching requirement to avoid salinization. Hammond and co-workers (1981a) suggested that a near ideal strategy in humid regions like Florida where irrigation water is not necessary for salinization control, would be to start the growing season with a soil water profile near its maximum retention capacity, allow it to be depleted by about 50% or more at harvest, while maintaining a season-long rainfall and irrigation distribution pattern which would prevent any plant water stress and any loss by deep drainage. The major difficulty in

putting this ideal strategy in practice is, first of all, the inevitable high drainage rates which would occur at the beginning of the season as a result of high water contents and shallow rooting depths. Secondly, the unpredictability of rainfall on a long-term basis during the growing season makes it practically impossible to avoid significant losses through deep percolation. The heaviest, though quite erratic, rainfall in Florida usually occurs during June through October when the amount of rainfall exceeds ET (Jones et al., 1984).

Measuring Soil Water Flow

The flux density of water (or flux) can be defined as the volume of water flowing through a unit cross-section of soil per unit time. The basic relationship describing water flow through saturated soils was postulated by Henry Darcy (Darcy, 1856). In 1931, Richards extended the formulation of Darcy's law to unsaturated flow by combining the principles of mass conservation and momentum. Water flux in a vertical one-dimensional soil body can be expressed according to Darcy's law as

$$q = - K\ (dH/dZ) \qquad [1]$$

where q is the soil water flux (L/T), H the hydraulic head (H = h - Z, where h is the matric potential), K a proportionality factor called hydraulic conductivity (L/T), Z the vertical distance or depth (positive downward) (L), and dH/dZ the hydraulic gradient (L/L). To describe conditions of unsaturated, unsteady, isothermal, nonhysteretic flow during drainage Eq. [1] must be combined with the continuity equation (Eq. [2]). This yields a nonlinear partial differential equation known as the Richards equation (Eq. [3])

$$\partial\theta/\partial t = - \partial q/\partial Z \qquad [2]$$

$$\partial\theta(Z,t)/\partial t = \partial[K(\theta)\ \partial H(Z,t)/\partial Z]/\partial Z \qquad [3]$$

In the presence of an actively transpiring crop, Eq. [3] becomes (Feddes et al., 1978)

$$\partial\theta(Z,t)/\partial t = \partial[K(\theta)\ \partial H(Z,t)/\partial Z]/\partial Z + ET(Z,\theta,t) \qquad [4]$$

where θ is the volumetric soil water content (L^3/L^3), t time (T), $K(\theta)$ the unsaturated hydraulic conductivity of the soil as a function of soil water content (L/T), ET the volume of water taken up by plant roots per unit soil volume per unit time (L^3/L^2T), and the other terms as defined previously.

There are generally two approaches to evaluating the water uptake term ET:

(i) the microscopic approach, where the radial flow of water to individual roots is simulated by lines or narrow tube sinks regularly spaced in the soil (Molz et al., 1968; Lambert and Penning de Vries, 1973; Hillel et al., 1975);

(ii) the macroscopic approach in which the whole rhizosphere is treated as a diffuse sink term (Molz and Remson, 1970 and 1971; Nimah and Hanks, 1973a and 1973b; Feddes et al., 1978). The relative merits of the two methods were discussed by Hillel and co-workers (1975). The major problem encountered in modeling the soil-water uptake by plant roots is the inherently complicated space-time relationship involved, as outlined by many investigators, including Hillel (1977). Those models usually require input parameters that are neither readily available, nor easily estimable with sufficient accuracy.

Even Eq. [3] which does not consider the sink term is not easy to solve analytically for most initial and boundary conditions that apply to field soils. This has

led to the development of various approaches for estimating water flux under field conditions. Wagenet (1986) identified four types of approaches: (1) direct measurements using soil water flux meters (Cary, 1968 and 1970; Dirksen, 1972 and 1974); (2) flux estimation based on the application of the continuity principles (Richards et al., 1956; Nielsen et al., 1964; Rose and Stern, 1967; Rose et al., 1965; Watson, 1966); (3) numerical models which provide approximate solutions of Eq. [3] using finite-difference and finite-element methods (Carnahan et al., 1969; Hillel et al., 1975; Ames, 1977; Watts and Hanks, 1978; Tillotson and Wagenet, 1982); (4) methods based on analytical solutions combined with scaling techniques (Warrick et al., 1977a and 1977b; Simmons et al., 1979).

Flux meters are devices installed in the soil to measure directly the volumetric water flux at a given depth in the soil profile. They can be subject to various kinds of problems including the localized nature of the measurement, the disruption of the soil during installation, interruption of normal soil water flow patterns, and divergence or convergence of streamlines of water due to the difference in hydraulic conductivity between the meter and the surrounding soil.

Methods (3) and (4) generally require complicated mathematical formulations and data-intensive modeling techniques not always compatible with soil water management constraints in agricultural fields. For such applications, methods based on continuity principles, when adequately used, can provide useful tools for characterizing soils in situ.

Field Measurement of Unsaturated Hydraulic Conductivity

Instantaneous profile method

Richards' equation which describes one-dimensional, isothermal, nonhysteretic, unsaturated, transient flow of water during drainage has been used extensively to determine unsaturated hydraulic conductivity and diffusivity *in situ*, over the water content range of interest for most practical applications. The advantages of the method over laboratory methods are the preservation of field structure and a larger area of measurement. As stated by Davidson et al. (1969), what the method loses in resolution as compared to laboratory determinations, it gains in validity. Furthermore, the data collected can also be used for the determination of soil water characteristic curves. The method requires very few assumptions since it is based on Darcian analysis of transient soil water content and hydraulic head profiles during vertical internal drainage following a heavy rainfall or irrigation. The approach was first initiated by Richards and Weeks (1953), then Richards et al. (1956). Other researchers (Nielsen et al., 1964; Rose et al., 1965; Watson, 1966) then improved it to its present form, which is known as the instantaneous profile method (IPM). There are many variations in the application of the method which has been used by several investigators for field water flow studies (Van Bavel et al., 1968*a* and 1968*b*; Hillel et al., 1972; Nielsen et al., 1973). The approach used herein is based on the following initial and boundary conditions:

- at time $t = 0$, the soil water flux is assumed constant throughout the soil profile for depths $0 \leq Z \leq L$;
- for $t > 0$, the flux at the soil surface is nil.

The method applies to field conditions where the water table is nonexistent or deep enough not to interfere with drainage. The experiment is usually done in the absence of any water source or sink and requires continuous and concurrent measurements of the soil water content and hydraulic head.

The integration of the unsaturated flow equation once with respect to depth between the limit of Z = 0 and any depth of interest, say Z = L yields for a given time

$$\int_0^L [\partial\theta(Z,t)/\partial t]dZ = K(\theta)\ \partial H(Z,t)/\partial Z\,\Big|_L \quad - K(\theta)\ \partial H(Z,t)/\partial Z\,\Big|_0. \qquad [5]$$

If the soil surface is covered to prevent any flux across the upper boundary, then the second term of the right hand side of Eq. [5] is zero. The equation can then be simplified to

$$\int_0^L [\partial\theta(Z,t)/\partial t]dZ = K(\theta)\ \partial H(Z,t)/\partial Z\,\Big|_L. \qquad [6]$$

The left hand side of Eq. [6] represents the rate of water loss from that portion of the profile above the depth Z = L. This rate can be determined in the field from successive water content measurements. The right hand side of Eq. [6] represents the flux q_L at the depth Z = L. The hydraulic head profiles for different times are measured with tensiometers or any other soil water pressure-sensing devices installed at selected depths. Instantaneous hydraulic gradients $\partial H/\partial Z$ can therefore be calculated. Solving Eq. [6] for K(θ) explicitly, yields

$$K(\theta) = \frac{\int_0^L [\partial\theta(Z,t)/\partial t]dZ}{\partial H(Z,t)/\partial Z\,\Big|_L}. \qquad [7]$$

Eq. [7] states that the unsaturated hydraulic conductivity K, for a specified depth, say $Z = L$, can be determined as a function of volumetric water content θ if the change in water content with time over a given depth is divided by the hydraulic gradient at the specified depth.

A finite difference technique can be used to evaluate $K(\theta)$ at discrete times and depths; θ and $\partial H/\partial Z$ can be averaged in both space and time at selected depths and times during drainage.

Let $\Delta\theta = (\theta_{i+1} - \theta_i)$ and $\Delta t = (t_{i+1} - t_i)$ where i represents a time value, $\Delta\theta$ the change in water content during the time interval Δt.

The average hydraulic gradient over that time interval can be evaluated as

$$(\overline{\partial H}/\overline{\partial Z})|_L = (1/2)[\{(\partial H/\partial Z)|_L\}_{i+1} + \{(\partial H/\partial Z)|_L\}_i]. \qquad [8]$$

Eq. [7] can then be rewritten as

$$K(\bar{\theta}) = \frac{\int_0^L [(\theta_{i+1} - \theta_i)/(t_{i+1} - t_i)]dZ}{(1/2)[\{(\partial H/\partial Z)|_L\}_{i+1} + \{(\partial H/\partial Z)|_L\}_i]} \qquad [9]$$

where $\bar{\theta} = (1/2)\ (\theta_{i+1} + \theta_i)_L$

There are usually three options for obtaining the input data for Eq. [9]:

(i) both the volumetric water content, θ, and hydraulic head, H, can be measured simultaneously in the field;

(ii) θ may be measured directly in the field and the hydraulic head H (H = h-Z) inferred from soil water characteristic curves [h = f(θ)] determined independently on core samples;

(iii) the hydraulic head may be measured directly and θ inferred from soil water release curves.

The first option would be preferable even though some data smoothing may be necessary.

Simplified methods

Many investigators, including Black et al. (1969), Davidson et al. (1969), Nielsen et al. (1973) have observed that during redistribution of soil water following infiltration in a uniform soil profile in which evapotranspiration is prevented, the pressure head (h) tends to remain constant with depth. This led to the unit gradient assumption which has been used by many researchers for the determination of hydraulic conductivity in the field.

$$\partial H/\partial Z = \partial(h - Z)/\partial Z = \partial h/\partial Z - \partial Z/\partial Z = - \partial Z/\partial Z = - 1. \quad [10]$$

Eq. [7] can then be rewritten as

$$K(\theta)_L = \frac{\int_0^L [\partial\theta/\partial t]dZ}{\partial H/\partial Z} = - \int_0^L [\partial\theta/\partial t]dZ. \quad [11]$$

With the right hand side of Eq. [11] estimated by L ($\partial\theta^*/\partial t$) where θ^* is the average water content in the soil profile to depth L at a given time, Eq. [11] can be rewritten as

$$K(\theta)_L = - L\ (\partial\theta^*/\partial t) \quad [12]$$

where $\theta^* = (1/L) \int_0^L \theta(z,t)dz.$ [13]

During the redistribution phase following infiltration, θ^* can be estimated by (Richards et al., 1956; Ogata and Richards, 1957; Gardner et al., 1970; Chong et al., 1981)

$$\theta^* = a\ t^{b} \qquad [14]$$

where a and b are constants and t time counted from the initiation of drainage.

Substituting the derivative of Eq. [14] into Eq. [12] yields K as a power function of time t:

$$K(\theta)_L = -\ L\ b\ a\ t^{(b-1)}. \qquad [15]$$

Solving Eq. [14] for t, explicitly, and substituting in Eq. [15] gives $K(\theta)$ as a power function of the average water content θ^* (Chong et al., 1981)

$$K(\theta)_L = -\ L\ b\ a^{1/b}\ [\theta^*]^{(b-1)/b}. \qquad [16]$$

A similar relationship can be derived using the soil suction in place of water content. This method is known as the "CGA method" (Chong et al., 1981; Libardi et al., 1980).

Libardi and coworkers (Libardi et al., 1980) proposed a different simplifying approach to the Richards equation (Eq. [6]) which can be reduced to

$$L\ \partial\theta^*/\partial t = K(\theta)\ \partial H/\partial Z\,\big|_L \qquad [17]$$

where θ^* is the average water content to depth $Z = L$. The value of θ^* can be estimated by

$$\theta^* = a\,\theta + b \qquad [18]$$

where a and b are constants and θ the water content at a particular depth.

Assuming unit gradient and expressing K as an exponential function yields

$$K(\theta) = K_0 \exp\left(\beta\,[\theta - \theta_0]\right) \qquad [19]$$

where β is a constant, and K_0 and θ_0 are the values of K and θ during steady state infiltration, respectively. Deriving Eq. [18] and combining it with Eq. [17] where $\partial H/\partial Z = -1$, yield

$$- a\,L\,\partial\theta/\partial t = K_0 \exp\left(\beta\,[\theta - \theta_0]\right) \qquad [20]$$

where a, K_0, θ_0 and θ are for depth Z = L. The natural logarithm of Eq. [20] gives

$$\mathrm{Ln}\,|\,a\,L\,\partial\theta\,| = -\beta\,(\theta_0 - \theta) + \mathrm{Ln}\,K_0 \qquad [21]$$

which can be rewritten as

$$\mathrm{Ln}\,|\,L\,\partial\theta^*| = -\beta\,(\theta_0 - \theta) + \mathrm{Ln}\,K_0 \qquad [22]$$

Eq. [22] represents the working formula of the "Libardi-Flux" method (Libardi et al., 1980). The slope and the intercept of a semilog plot of the absolute value of $(L\partial\theta^*/\partial t)$ vs. $(\theta_0 - \theta)$ give a direct estimate of β and Ln K_0, respectively.

On the other hand, the integration of Eq. [20] at a given depth Z = L from the initial condition ($t = 0$, $\theta = \theta_0$) to ($t = t$, $\theta = \theta$) yields

$$\theta_0 - \theta = \frac{1}{\beta}\,\mathrm{Ln}\,(1 + \beta\,K_0\,t/a\,L). \qquad [23]$$

For $t >> 1$, Eq. [23] can be simplified to

$$\theta_0 - \theta = \frac{1}{\beta} \text{Ln } t + \frac{1}{\beta} \text{Ln } (\beta \, K_0 / a \, L) \qquad [24]$$

in which the right hand side represents a linear function of Ln t.

Eq. [24] represents the formulation of the"Libardi-theta" method (Libardi et al., 1980).

Soil-Water Characteristic Curve

The most important components of soil water potential are the pressure potential (h) and the gravitational potential (Z). The water retention function which relates a capacity factor, the water content, to an intensity factor, the water potential, is a fundamental part of the hydrodynamic characterization of soils. When expressed in energy per unit weight, water potential has dimension of length (e.g., cm of water). The $\theta(h)$ relation can be obtained either by desorption or sorption.

The $\theta(h)$ function is highly hysteretic, and usually the water content at a given pressure head for a wetting soil is less than for a draining soil (Haines, 1930; Topp, 1969; Pavlakis and Barden, 1972). The hysteresis effect may be attributed to several causes:

(1) geometric nonuniformity of the individual pores ("ink bottle effect");

(2) contact angle effect due to the fact that an advancing water meniscus tends to have a greater contact angle than in the case of a receding one;

(3) entrapment of air during wetting;

(4) swelling, shrinking, or aging phenomena which result in differential changes of soil structure, depending on the wetting and drying history of the soil.

The hysteresis effect is generally more pronounced in coarse-textured soils in the low-suction range where pores may empty at an appreciably larger suction than that

at which they fill (Hillel, 1980). The $\theta(h)$ relationship is also influenced by the initial water content of the soil. The two complete characteristic curves, from saturation to dryness and vice versa, are called the main branches of the hysteretic soil water characteristic curve. Draining a partially wetted (or rewetting a partially desorbed) soil will result in some intermediate curves called scanning curves, which may form loops between the main branches. The drainage curve that starts at complete saturation (θ_s) of the soil is called the initial drainage curve (IDC). As the soil drains, the matric potential decreases, and water content will approach a lower limit called the residual water content θ_r. On the other hand, the main wetting curve (MWC) is obtained by wetting a soil from θ_r until the pressure head approaches zero. The water content will then reach a value θ_0 called natural saturation or satiated water content which is less than the total porosity, θ_s, due to the presence of entrapped air. In most soils, θ_0 is about 0.8 θ_s to 0.9 θ_s in laboratory conditions (Klute, 1986) and should be even less in the field. The drainage curve obtained starting at θ_0 is the main drainage curve (MDC). It merges asymptotically with the IDC, then lastly with the MWC.

Because of the complexity of the $\theta(h)$ relationship, the hysteresis phenomenon has been generally ignored in most applications and the water characteristic curve usually reported is the desorption curve. Recent numerical methods of solving the flow equation are beginning to take into account hysteresis information (Mualem, 1974), but such methods are difficult to apply to field conditions. Smiles et al. (1971) and Vachaud et al. (1972), working with 60-cm long horizontal and vertical sand columns, showed that during transient nonhysteretic flow of water, the soil moisture characteristic curve was a unique function during sorption from a particular initial water content, but during desorption there was a multiplicity of curves, depending on the magnitude of

the imposed water content change and also on the speed with which static equilibrium was achieved after the change. Furthermore, they also reported that the dynamic $\theta(h)$ curve obtained by simultaneous measurement of θ and h during transient flow was different from that determined by measuring the static equilibrium water content following each of an infinetely large number of infinetely imposed increments in h (or during steady flow experiments). These findings were in agreement with those of Topp et al., (1967) but not with those of Watson (1965), whose static and dynamic $\theta(h)$ curves were identical. This brings some uncertainty and doubt on the adequacy of extrapolating laboratory-determined water release curves to agricultural fields in which steady state conditions seldom occur.

Because of the inconvenience of using tabulated data, many investigators have derived empirical and analytical equations describing the $\theta(h)$ relationship (Brooks and Corey, 1964; Simmons et al., 1979; van Genuchten, 1980). The van Genuchten formula

$$\theta(h) = \theta_r + (\theta_s - \theta_r)/(1 + \alpha \mid h \mid^n)^m \qquad [25]$$

has been used successfully in recent years by many investigators. θ_s and θ_r represent saturated and residual water contents respectively, and α, n and m are parameters that can be determined by fitting data with Eq. [25]. McQueen and Miller (1974) have identified three linear segments on the $\theta(h)$ curve when θ and h are expressed on a linear and logarithmic scales, respectively. Such plottings can be useful for limited data ranges such as those obtained during internal drainage experiments.

Materials and Methods

In order to determine the hydraulic characteristics of the soil, two plots, 14 by 14 m, were selected in Unit 2 at the Irrigation Research and Education Park (IREP) in Gainesville. The soil is classified as a Millhopper fine sand, a member of the loamy, hyperthermic family of Grossarenic Paleudults (Calhoun et al., 1974) and has been under continuous and intensive cultivation for more than 40 years. The last crops of corn, sorghum and peanut were harvested just a few days before the beginning of the present experiment. All plant residues were removed from the soil surface. The selection of those two plots was based on their relative position (plot 9 on the WNW border and plot 16 on the ESE edge of Unit 2), the depth to the argillic horizon (110 to 180 cm), their level topography and their overall representativeness of the physical characteristics of the whole unit which consists of 24 similar plots.

Field Procedures

Five aluminum neutron access tubes and five sets of tensiometers (at 15, 30, 45, 60 and 90 cm depths) were installed in the inner 2.8 by 2.8 m central square of each plot. Irrigation water was applied using a solid-set sprinkler system at a rate varying from 1.8 on the borders to 3.1 cm/hour on the center of the plot where all the monitoring devices were located. Water was applied in four settings of 90 minutes each, resulting in a total irrigation depth of about 18 cm of water in the central part. No effort was made to saturate the profile, the rationale being to simulate the hydro-dynamic conditions that prevail in that land during its normal use. After each irrigation session, tensiometer readings were taken in order to locate the depth of the wetting front. Irrigation was stopped after the wetting front had crossed the 90 cm

depth and the pressure head profiles were relatively uniform at all depths. Each plot was then covered entirely with a 0.5-cm polyethylene sheet for 42 days to prevent any evaporation.

Water content and hydraulic head were measured simultaneously at variable time intervals using a neutron probe and the tensiometers mentioned above. The neutron probe used was a Troxler 1651 with 100 mC Am-Be source. The calibration curve determined in previous studies in the same site was

$$\theta\% = 24.6645 \text{ CR} - 2.626$$

where CR is the count ratio (count in the soil over count in the probe shield) and θ the volumetric water content in per cent. The coefficient of correlation was $r = 0.9959$.

Hydraulic heads were read directly in millibars with a digital pressure meter linked to a pressure transducer (tensimeter imported from Switzerland by Soil Measurement Systems, Las Cruces, NM) which made contact with the tensiometer chamber through a hypodermic needle inserted through a septum stopper.

Data were collected in the same sequence, starting with profile 1 in plot 16 and ending with profile 5 in plot 9 about one hour later. Thirty days after the initiation of drainage 3-cm undisturbed core samples were taken at 15, 30, 45, 60, 75 and 90 cm depths for laboratory hydraulic characterization of the soil at each of the ten locations of the neutron access tubes and tensiometers.

Data Handling

The raw water content (θ) and pressure head (h) data collected at each depth in each profile were smoothed separately using the following empirical polynomials (Bruce et al., 1983)

$$\theta(t) = A + B\,t + C\,t^2 + D\log t + E\log t^2 + F/t^{1/2} + G/t + H/t^2 + I/t^4 \qquad [26]$$

$$h(t) = A' + B't + C't^2 + D'\log t + E'\log t^2 + F'/t^{1/2} + G'/t + H'/t + I'/t^4 \qquad [27]$$

where t is the time in days after the initiation of drainage. The raw data were fitted to those equations using the stepwise regression procedures of the Statistical Package SAS to determine coefficients A (or A′) through I (or I′). Any term found to be insignificant was removed from the model. All the fitted curves had coefficients of determination greater than 0.99. The $\theta(t)$ and h(t) equations obtained were then used to generate predicted water content and pressure head data which were used for the calculations of unsaturated hydraulic conductivity and for water release curve determination. A complete listing of those data for the ten profiles is given in Appendix A.

Computations of hydraulic conductivity were made according to the procedure explained in Eq. [5] through [9]. Computed values of $K(\theta)$ and K(h) were then fitted to empirical functions using the Statistical Package SAS. Those fitted functions were then compared to relationships generated by the Chong et al. (1981) and the Libardi et al. (1980) methods.

The $\theta(h)$ relationships using field and laboratory data were fitted according to the van Genuchten model using the nonlinear procedures of SAS (1985). Laboratory-determined $\theta(h)$ data are listed in Appendix B.

Results and Discussion

Simplified Methods

Tables 1 through 3 and figures 1 through 3 give the computational steps for the determination of the different parameters necessary for calculating hydraulic conductivity values based on Chong et al. (1981) (table 1 and fig. 1) and Libardi et al. (1980) (tables 2 and 3; fig. 2 and 3) methods. The data generated by those models were then fitted to a linear equation on a logarithmic plot. Libardi methods yield saturated hydraulic conductivity values which are unrealistically high. Furthermore, the two methods differ in their estimation of K_s and β.

Instantaneous Profile Method

Figures 4a through d represent unsaturated hydraulic conductivity as a function of pressure head on a semi-logarithmic plot. The data points represent the calculated values of K using the Darcian analysis of water flux (IPM). The observed data are quite well fitted by the regression lines at all the four depths shown.

Figures 5a-d through 7a-d show the relationships of K as a function of water content determined by the IPM, and compare the aforementioned method to the Chong and Libardi simplified models. The different parameters of the $K(\theta)$ functions for the 30, 45, 60 and 90 cm depths are summarized in table 4. A Student test was used for the comparison of slopes of the regression lines between the IPM equations and the others. With the exception of the Libardi-Flux at 30 cm depth, methods based on the unit gradient assumption produced $K(\theta)$ functions which were significantly different from the relationships obtained by the Darcian method ($p = 0.05$). This was

Table 1. Equations of the fitted functions of average volumetric water content from 0 to depth Z vs. time (days) after initiation of drainage for 10 profiles in Unit 2, IREP.

$$\theta^* = a\, t^{b}$$

Depth Z (cm)	a	b	n	R^2
15	0.05696	-0.18438	240	0.911
30	0.06333	-0.17628	240	0.911
45	0.07322	-0.16081	240	0.914
60	0.08074	-0.14806	240	0.921
75	0.08491	-0.14181	240	0.929
90	0.08714	-0.13916	240	0.933

Table 2. Equations of the fitted functions of average volumetric water content from 0 to depth Z vs. actual volumetric water content at that depth for 10 profiles in Unit 2.

$$\theta^* = a\,\theta + b$$

Depth Z (cm)	a	b	n	R^2
15	0.90429	0.00273	240	0.976
30	0.78778	-0.00379	240	0.975
45	0.88406	-0.01943	240	0.969
60	0.91117	-0.01503	240	0.949
75	0.87251	-0.00486	240	0.948
90	0.86228	0.00107	240	0.943

Table 3. Computed parameters necessary for the determination of unsaturated hydraulic conductivity functions by Libardi-Flux and Libardi-Theta methods.

$\theta_s = 0.37$

Libardi-Flux: $\mathrm{Ln} \mid Z\ \partial\theta^*/\partial t \mid = -\beta\ (\theta_s - \theta) + \mathrm{Ln}\ Ks$

Depth (cm)	β	Ks (cm/day)	n	R^2
15	102.9	7.68×10^{12}	229	0.809
30	83.8	5.31×10^{9}	230	0.819
45	90.2	9.51×10^{9}	230	0.838
60	95.1	4.87×10^{10}	230	0.865
75	92.2	3.73×10^{10}	230	0.869
90	86.5	1.17×10^{10}	230	0.869

Libardi-Theta: $\theta_s - \theta = (1/\beta)[\mathrm{Ln}\ t + (1/\beta)\ \mathrm{Ln}\ (\beta Ks\ /a\ Z)]$

Depth (cm)	β	Ks (cm/day)	n	R^2
15	138.8	9.90×10^{17}	200	0.654
30	104.1	2.82×10^{12}	200	0.657
45	111.5	4.42×10^{12}	200	0.675
60	120.5	7.28×10^{13}	200	0.786
75	115.3	3.08×10^{13}	200	0.843
90	109.1	9.57×10^{12}	200	0.845

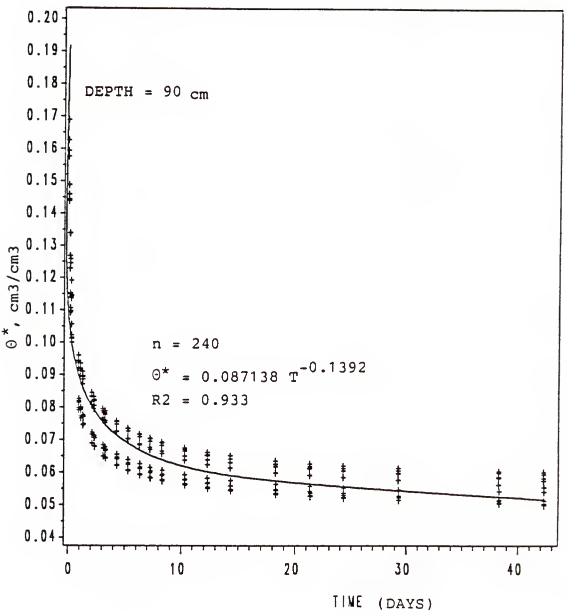


Fig. 1. Average volumetric water content to 90 cm depth versus time after initiation of drainage for 10 profiles in Unit 2, IREP.

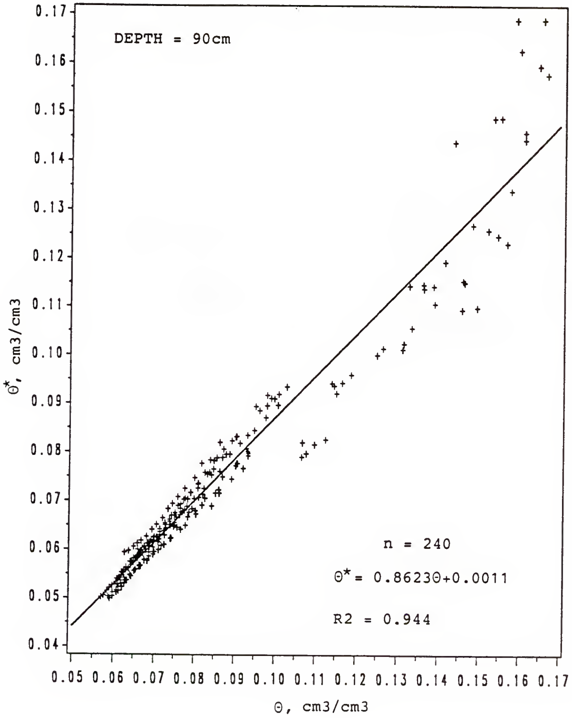


Fig. 2. Average volumetric water content to 90 cm depth versus volumetric water content at 90 cm depth for 10 profiles in Unit 2, IREP.

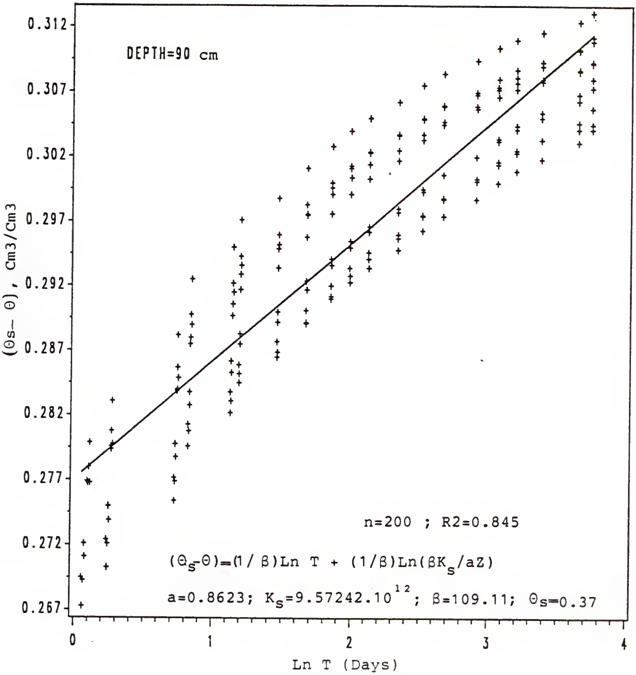


Fig. 3a. Determination of parameters necessary for the calculation of unsaturated hydraulic conductivity by the Libardi-theta method at 90 cm depth for 10 profiles in Unit 2, IREP.

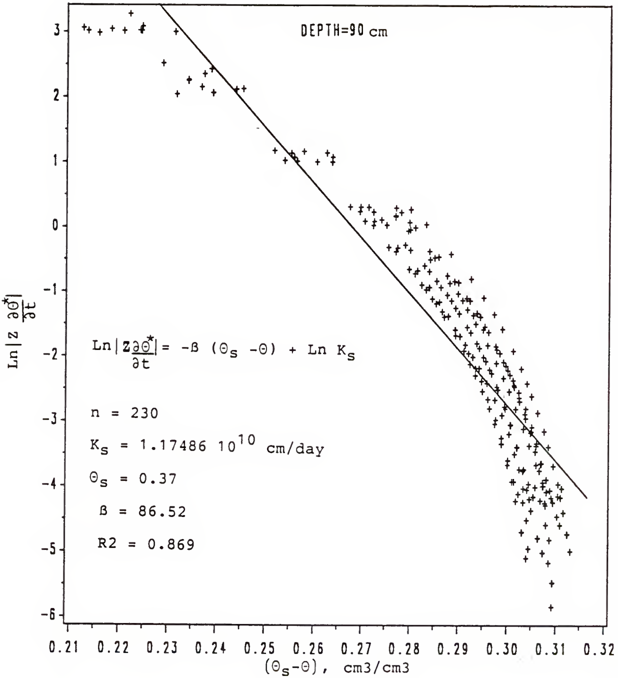


Fig. 3b. Determination of parameters necessary for the calculation of unsaturated hydraulic conductivity by the Libardi-flux method at 90 cm depth for 10 profiles in Unit 2, IREP.

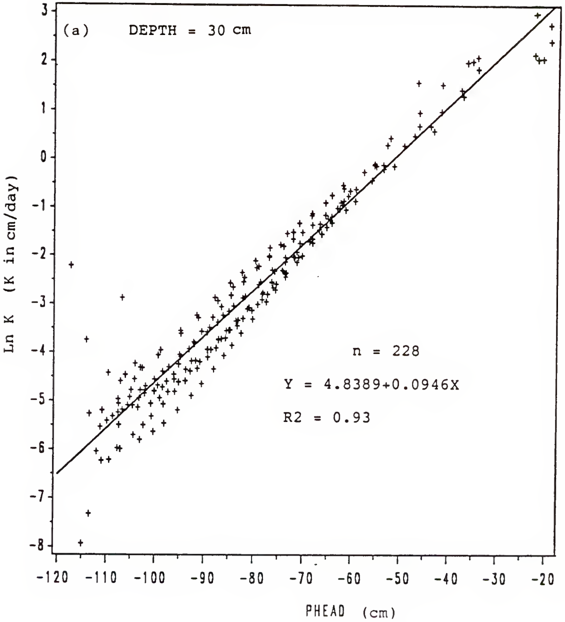
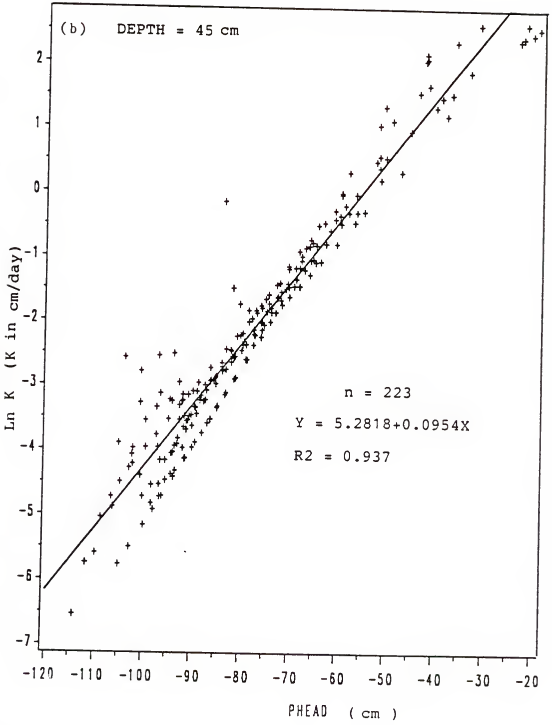


Fig. 4. Hydraulic conductivity as a function of pressure head for 10 profiles in Unit 2, IREP.



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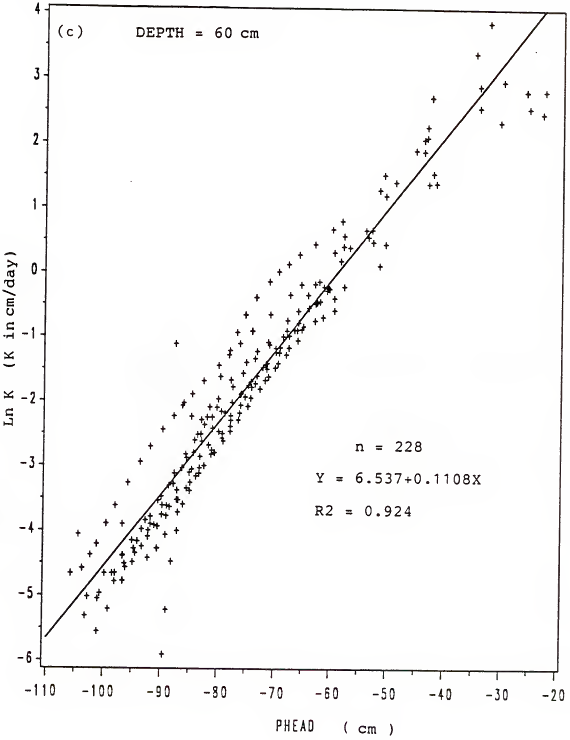

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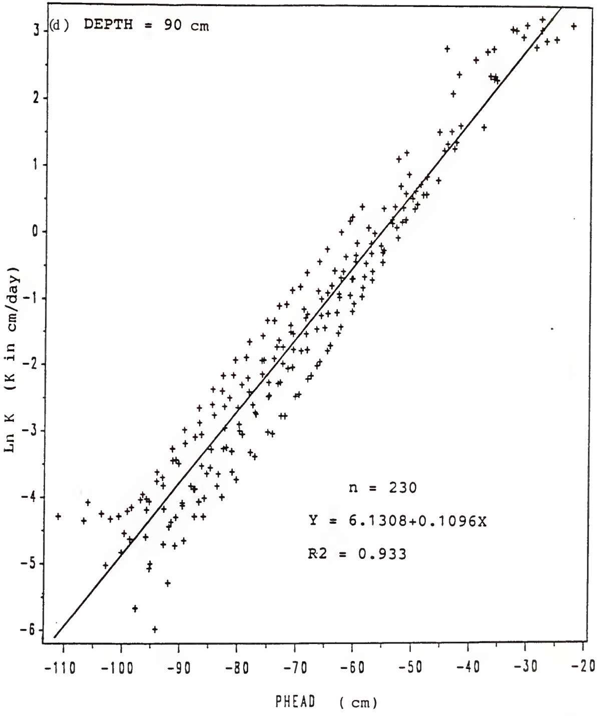

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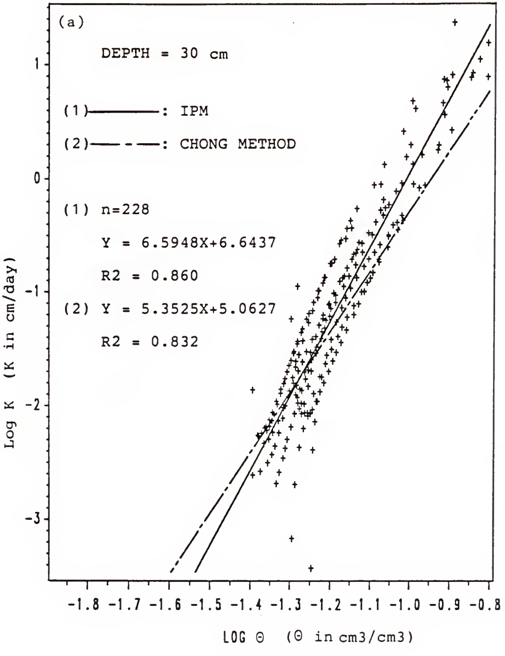
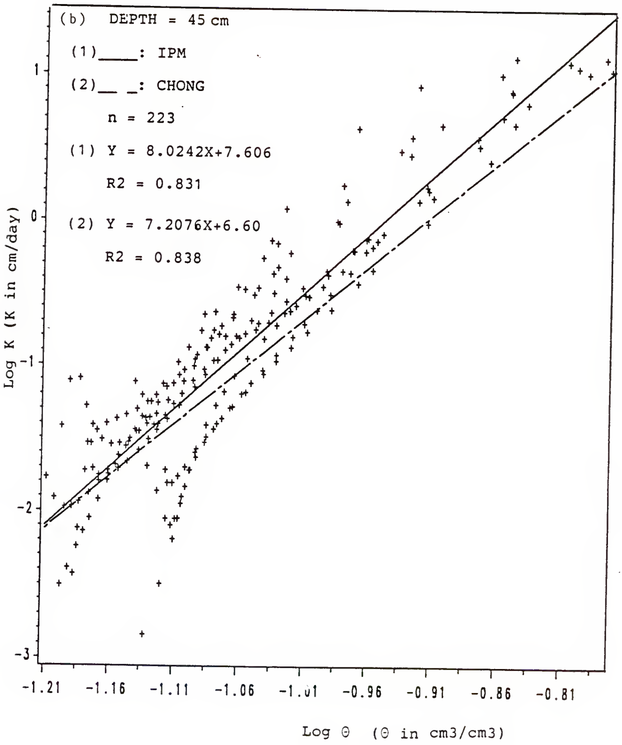


Fig. 5. Comparison of unsaturated hydraulic conductivity functions determined by the instantaneous profile method (IPM) and Chong method (CGA) for 10 profiles in Unit 2, IREP.



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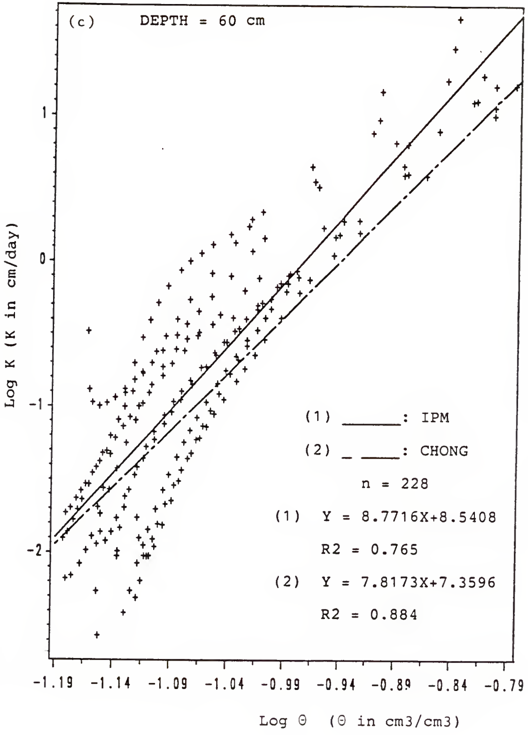

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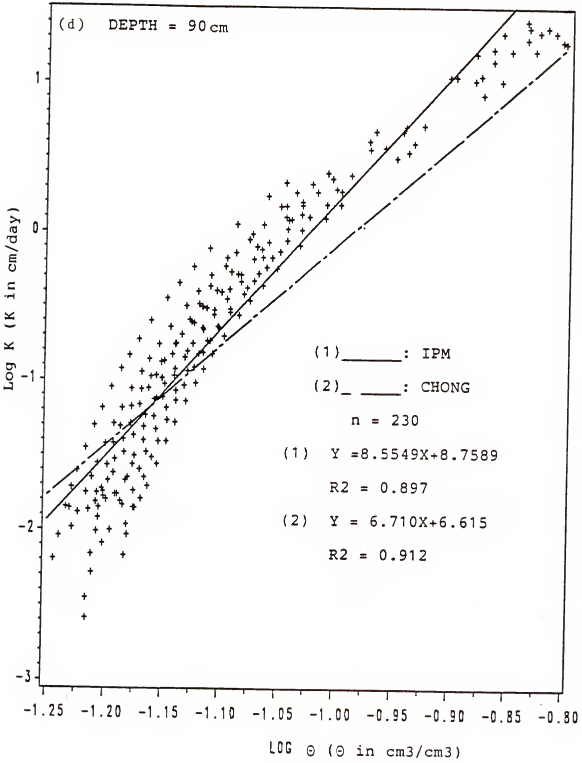

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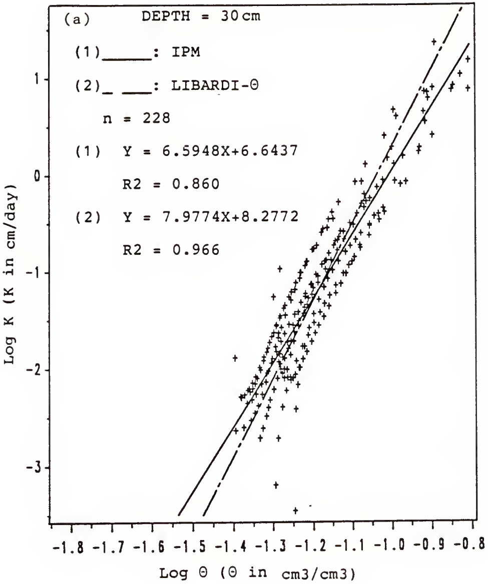
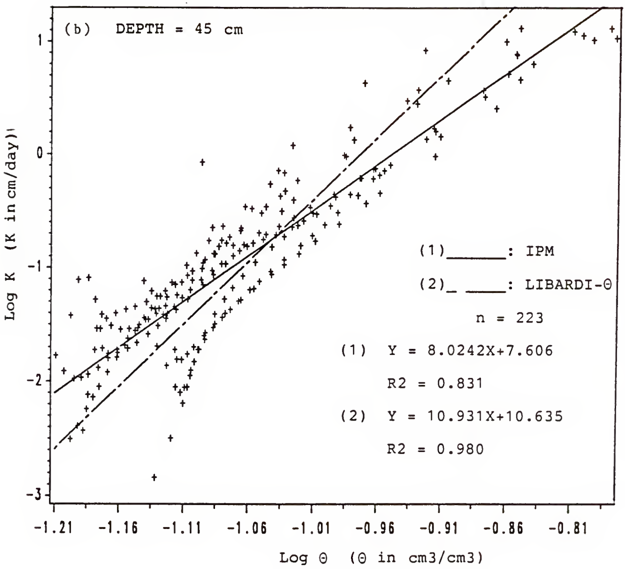


Fig. 6. Comparison of unsaturated hydraulic conductivity functions determined by the instantaneous profile method (IPM) and the Libardi-theta method for 10 profiles in Unit 2, IREP.



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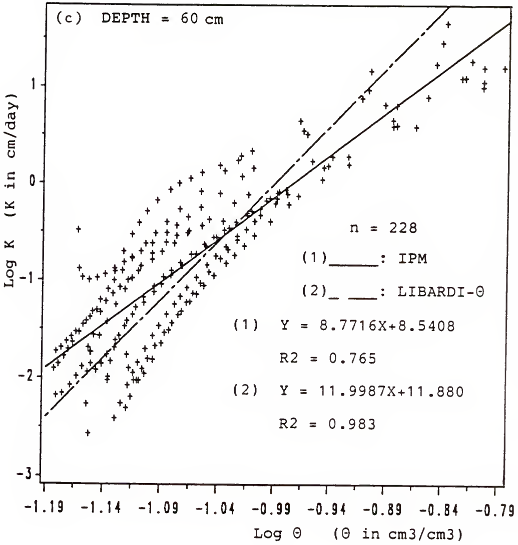

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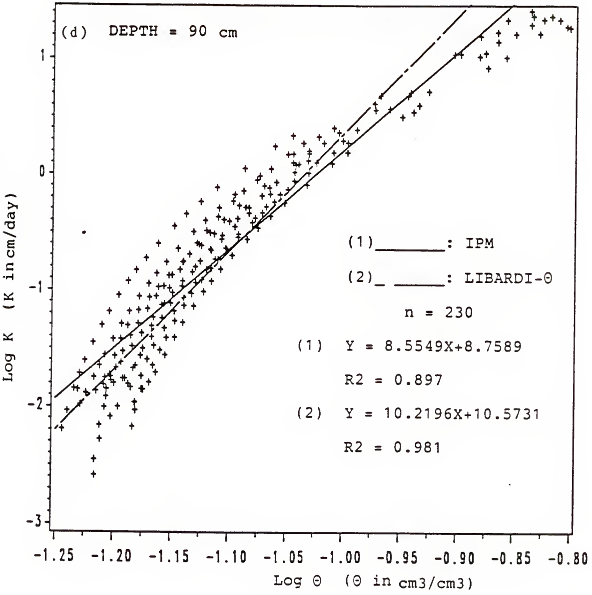

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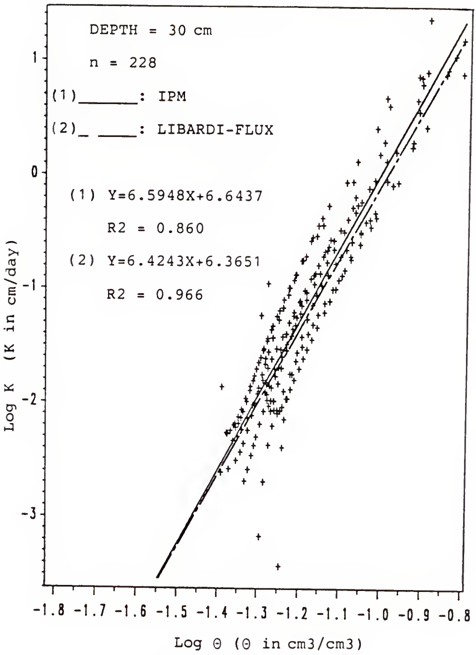
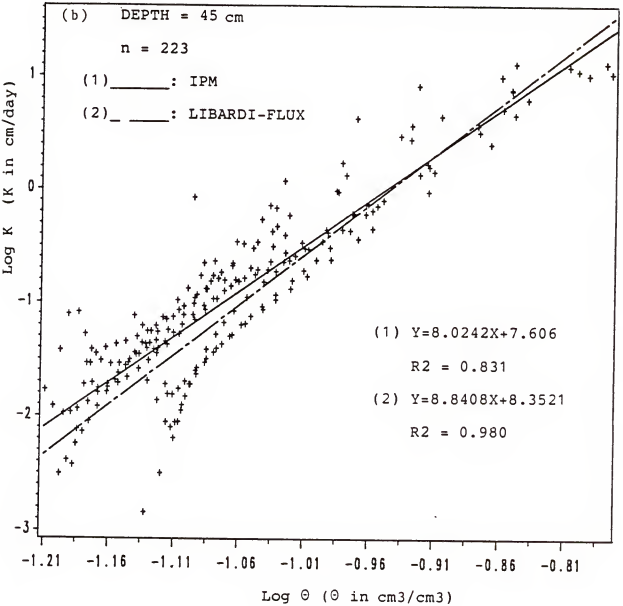


Fig. 7. Comparison of unsaturated hydraulic conductivity functions determined by the instantaneous profile method (IPM) and the Libardi-flux method for 10 profiles in Unit 2, IREP.



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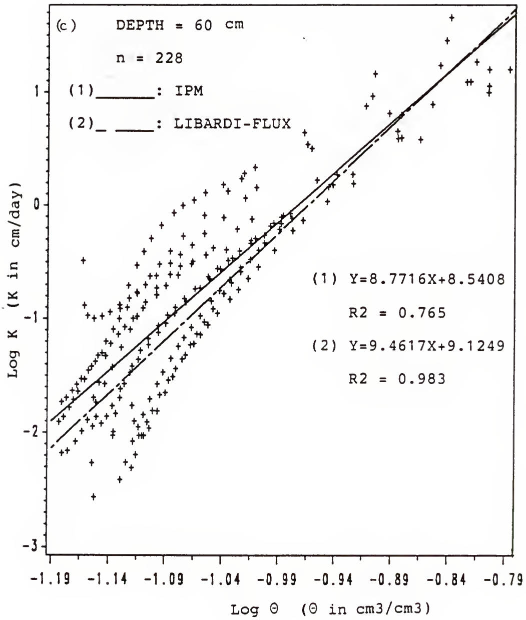

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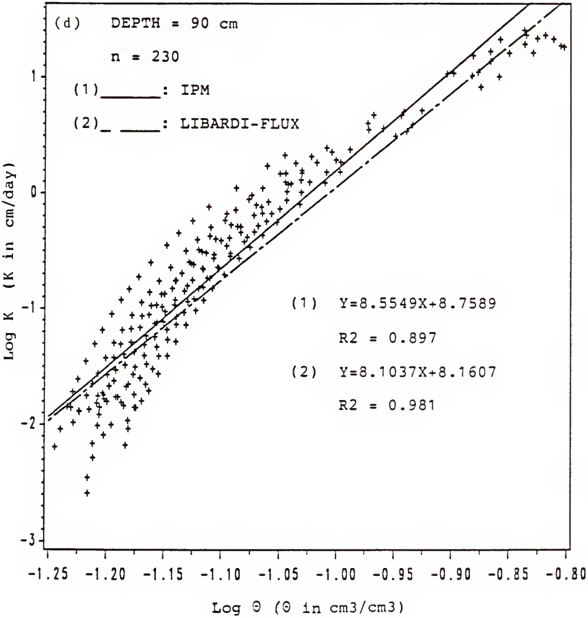


Fig. 7.- Continued

Table 4. Comparison of some methods for determining unsaturated hydraulic conductivity functions.

$$\text{Log } K(\theta) = a + b \text{ Log } \theta$$

Soil depth (cm)	Method	a	b	R^2	t-value
	IPM	6.64	6.59	0.860	-
	CG	6.71	6.65	0.863	0.24
30	CGA	5.06	5.35	0.832	5.20**
	Li-Th	8.28	7.98	0.966	6.79**
	Li-Fl	6.36	6.42	0.966	0.87
	IPM	7.63	8.05	0.832	-
	CG	8.54	8.94	0.871	2.74**
45	CGA	6.60	7.21	0.838	2.52*
	Li-Th	10.63	10.93	0.980	10.98**
	Li-Fl	8.35	8.84	0.980	3.17**
	IPM	8.54	8.77	0.765	-
	CG	9.46	9.71	0.908	2.45*
60	CGA	7.36	7.82	0.884	2.55*
	Li-Th	11.88	12.00	0.983	9.49**
	Li-Fl	9.12	9.46	0.983	2.07*
	IPM	8.76	8.55	0.897	-
	CG	8.58	8.43	0.923	0.51
90	CGA	6.61	6.71	0.912	7.80**
	Li-Th	10.57	10.22	0.980	7.75**
	Li-Fl	8.16	8.10	0.980	2.18*

* and ** indicate a significant difference between the slope of the function determined by the Instantaneous Profile Method (IPM) and that of other methods at p=0.05 and p=0.10, respectively.

predictable if one considers that the unit gradient assumption during drainage represents an ideal situation of perfectly uniform profiles both with regard to pore-size distribution and hydraulic conductivity. The high values of R^2 in the simplified models are not meant to be misleading. They represent the goodness of fit of the data predicted by the model (which were omitted) to the linear equations. Looking at figures 8a-d reveals that the hydraulic gradients were quite variable both with time and with depth at all the ten sites. Similar variabilities have been reported recently by Ahuja et al. (1988) working in various types of soils including fine sands.

By pooling all the data, the calculated average gradient was 0.856 ± 0.02 ($p = 0.05$) and was found to be significantly different from unity. Plugging that value into the water flow equation resulted in the constant gradient assumption (CG) which shows some agreement with the IPM (figures 9a-d and table 4). But this assumption does not have the attractiveness of the unit gradient concept since the gradient has to be measured anyway.

$K(h)$ relationships showed less variability than the $K(\theta)$. But as reported by many investigators, the $K(h)$ function is generally more hysteretic than the $K(\theta)$, making the latter relationship preferable in situations of repeated cycles of wetting and drying as occurs in most agricultural soils.

Water Release Curves

Laboratory and field-determined $\theta(h)$ relationships are represented in figures 10a-e. One should recall that irrigation was applied with the purpose of duplicating normal water management conditions as they prevail during crop growing seasons in that soil. All the profiles at all depths exhibited relatively low water contents at high

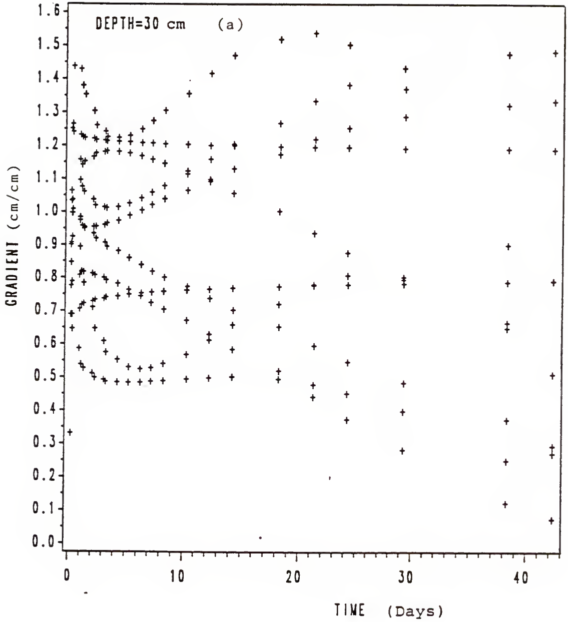
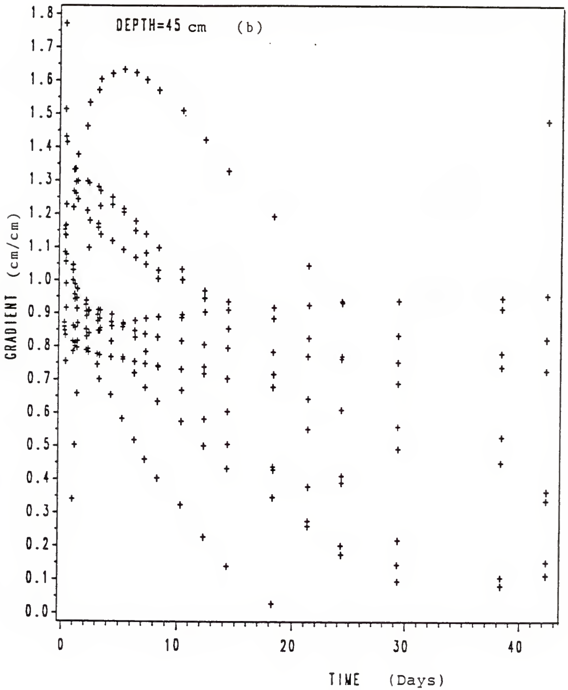


Fig. 8. Hydraulic gradient (cm/cm) versus time (days) after initiation of drainage for 10 profiles in Unit 2, IREP.



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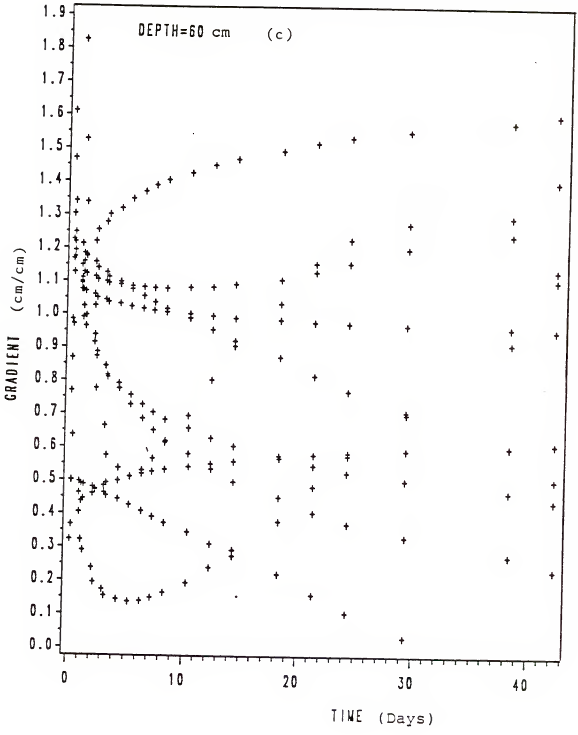

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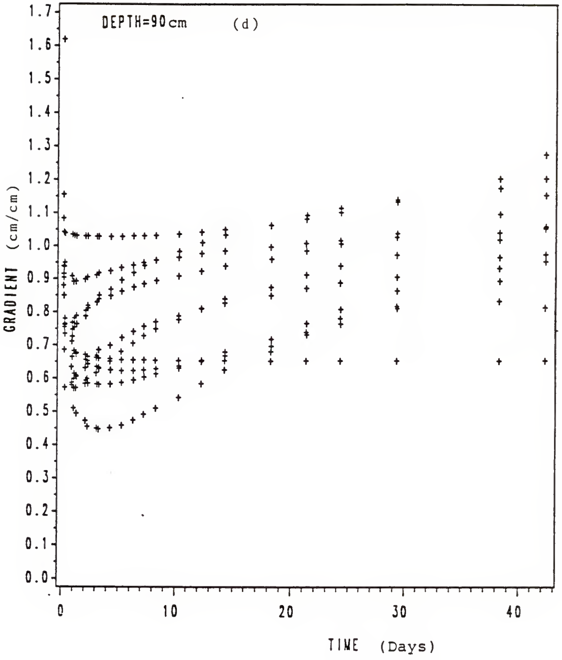

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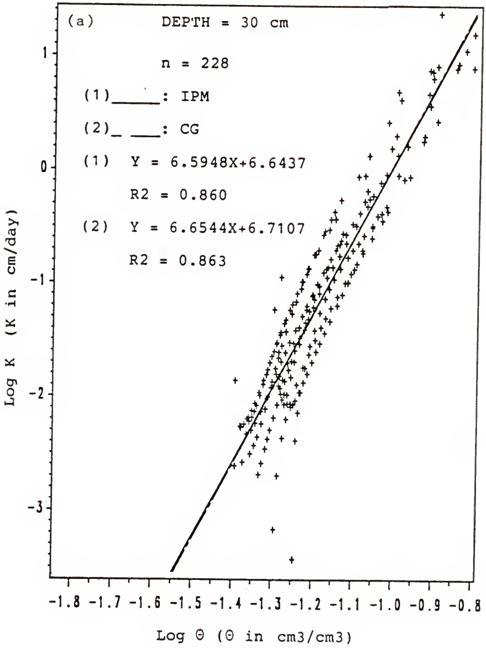
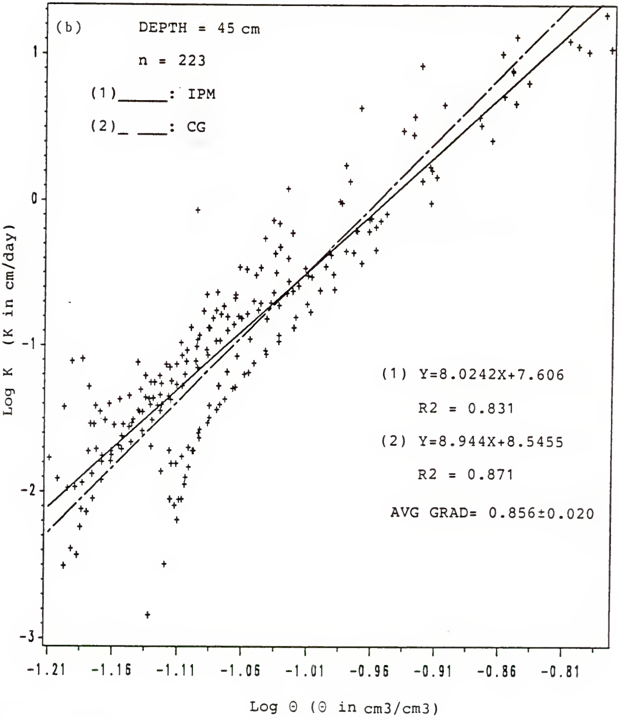


Fig. 9. Comparison of unsaturated hydraulic conductivity functions determined by the instantaneous profile method (IPM) and by the constant gradient assumption method (CG) for 10 profiles in Unit 2, IREP.



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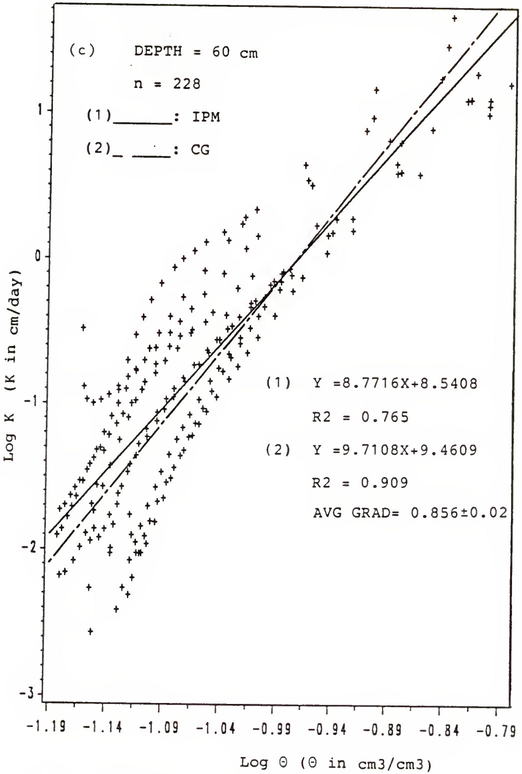

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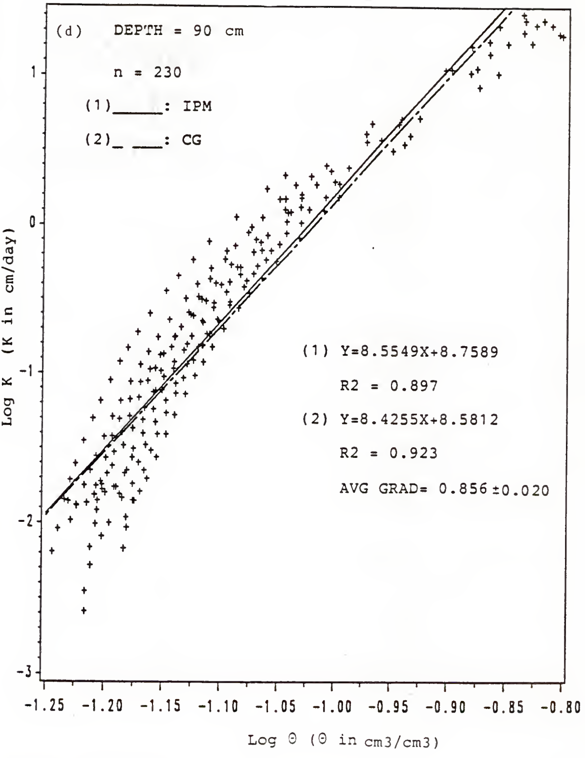

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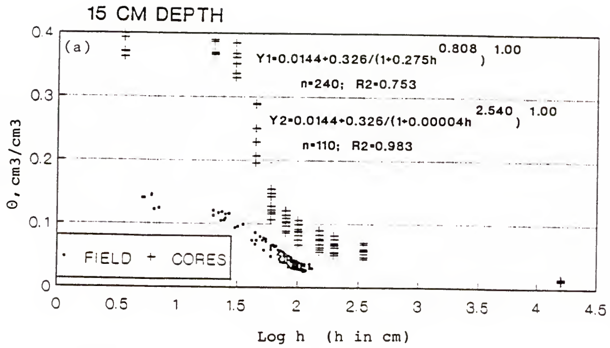


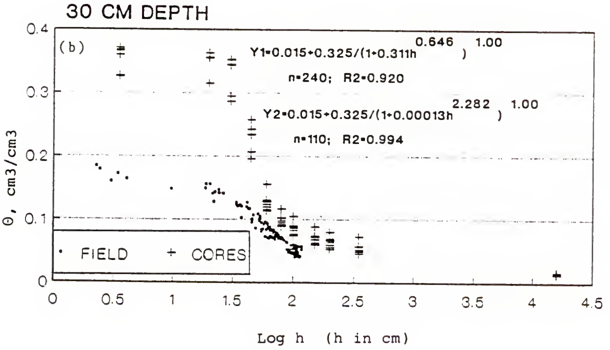
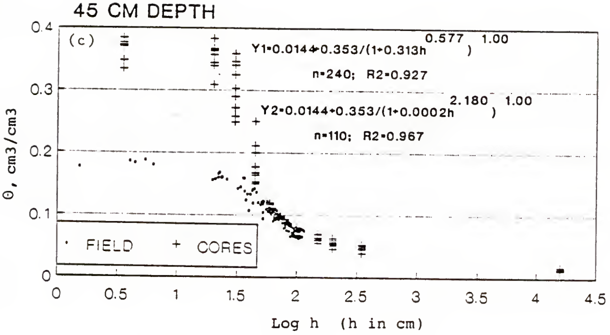


Fig. 10. Water release curves for 10 profiles in Unit 2, IREP. Equations represent the fitted curves for the field (Y_1), and core sample (Y_2) data points using the van Genuchten model.



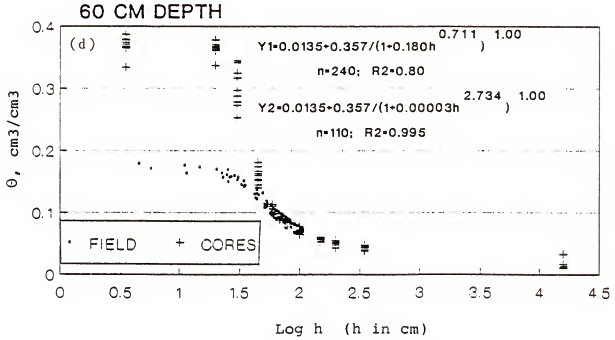


Fig. 10.- Continued

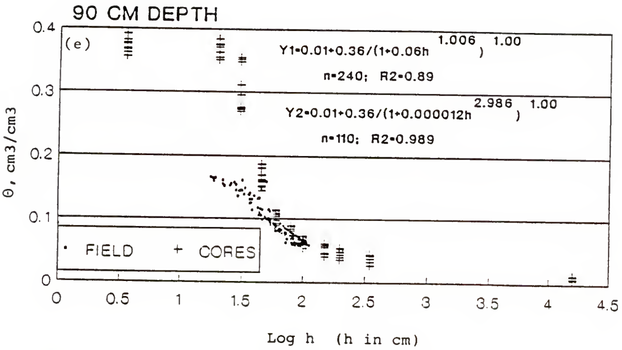


Fig. 10.- Continued

matric potential. Water content values were a little less than 20% by volume at suction values near zero (h = 0 corresponds to a water content of the soil at satiation). This resulted in apparent satiation water contents which were about 50% of the real saturation water content. Most of the discrepancies observed are probably due to the entrapment of air, a major reason for the difficulty in obtaining saturation under field conditions. On the other hand, coarse-textured, well-drained soils desaturate quickly, following termination of water input. It is also important to note the low values of water content as the matric potential decreases below -100 cm, and the good agreement between field and laboratory data (at 45, 60 and 90 cm depths) within the range of interest for agricultural purposes. At 15 and 30 cm depths, core data systematically show a higher water content at any given suction.

Within the range of water contents commonly encountered in natural agricultural fields the $\theta(h)$ relationship can be fairly well represented by simple empirical functions (exponential or power functions). Such functions can be linearized, and therefore present a major advantage for computer time over closed-form formulas. Figures 11a-d represent $\theta(h)$ as an exponential function:

$$\theta = a \exp(b\ h)$$

$$\text{Log}\ \theta = \text{Log}\ a + \text{Log}\ (\exp[b\ h])$$

$$\text{Log}\ \theta = A + B\ h\ .$$

The higher values of coefficients of determination obtained when using van Genuchten's model are partly due to the greater number of parameters involved.

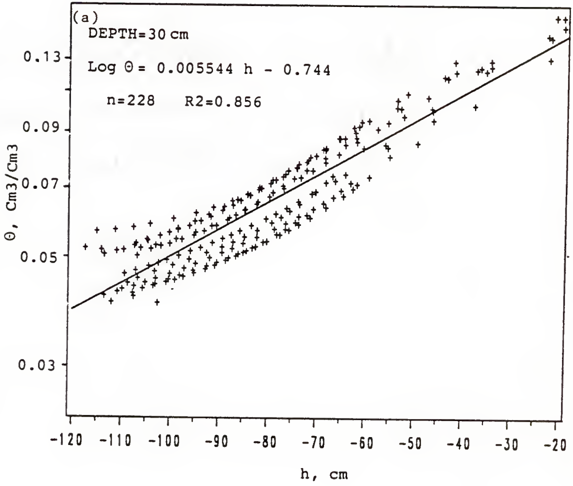


Fig. 11. Water release curves for 10 profiles in Unit 2. Field data points were fitted to a linearized exponential function.

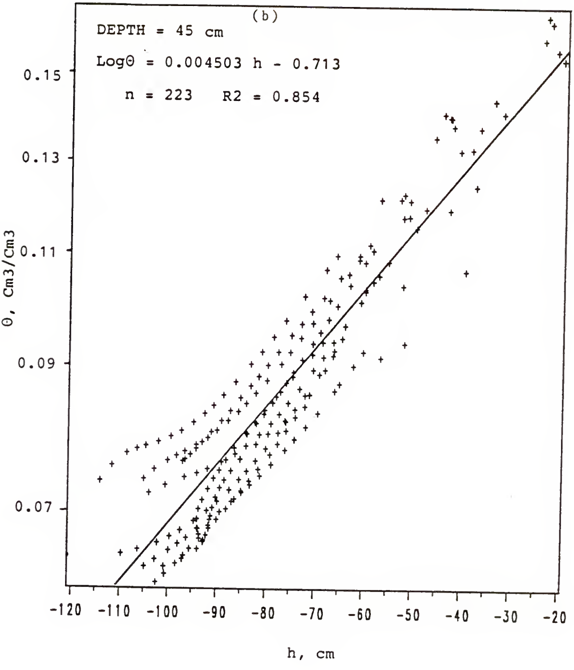


Fig. 11.- Continued

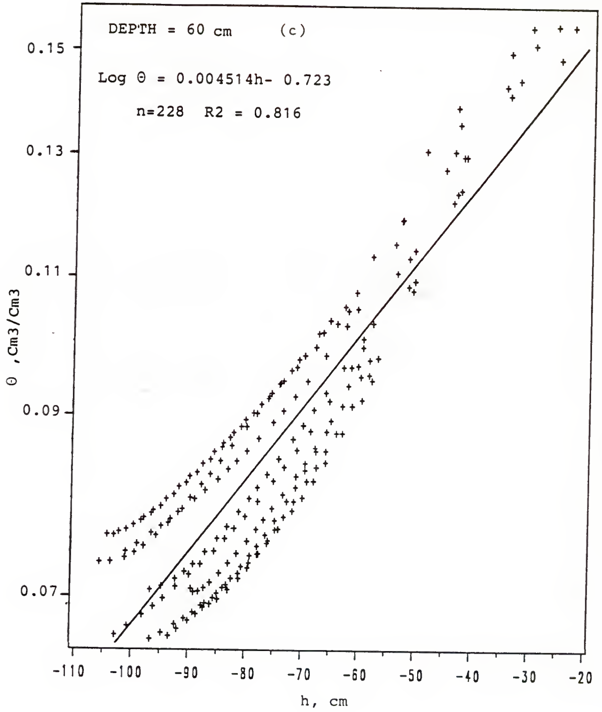


Fig. 11.- Continued

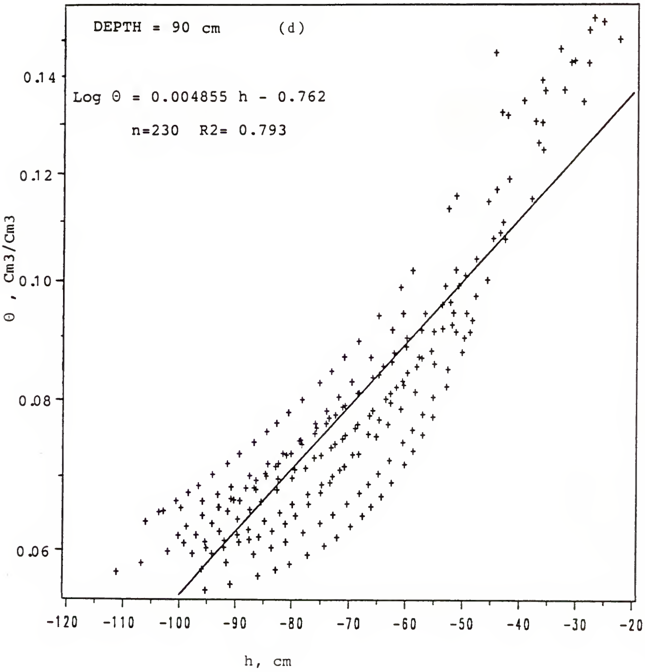


Fig. 11.- Continued

Summary and Conclusions

The instantaneous profile method (IPM) has been repeatedly described by many investigators and has become a standard procedure for field-oriented water flow studies. But the method presents some limitations due to technical problems (instrument errors) as well as inherent soil spatial variability. Stone (1972), Baker et al. (1974), and Flühler et al. (1976) among others have produced critical analyses of the error propagation involved in determining hydraulic conductivity using IPM in the field. Smoothing θ and h data with regard to time can help reduce some of the error due to instrumentation effects. Flühler et al. (1976) suggested that errors resulting from tensiometer readings become significant at low hydraulic gradients (< 0.3 cm/cm). Those errors may be preponderant during the early stage of the transient drainage. On the other hand, errors in water content measurements become dominant when drainage is greatly slowed.

Errors on $K(\theta)$ determinations are relatively small in the wet range of water contents where they can amount to 20-30% of K values. Such errors may be larger in the drier range of water contents. Any other field-oriented method would most likely result in similar uncertainties.

The simplified methods based on the unit-gradient assumption happen to be more restrictive in their conditions of applicability. There is nothing wrong in the unit gradient assumption as such, but what is inadequate is the way it has been used as a panacea for solving all unsaturated field water flow situations.

Field- and laboratory-determined moisture release curves agreed at 45, 60 and 90 cm depths only at medium, and probably, low values of pressure head, illustrating the influence of the initial water content, and presumably also of the magnitude of

$\partial h/\partial t$, on the $\theta(h)$ relationship. The field-determined $\theta(h)$ is therefore not unique. Its only merit would be that, at high pressure heads, it may describe the $\theta(h)$ relation more appropriately than the laboratory-determined curve during the normal agricultural use of that land.

CHAPTER 3
SOIL WATER BALANCE IN A CROPPED FIELD

Introduction and Literature Review

The concept of potential evapotranspiration stems essentially from the fact that when soil water is not limiting, the rate of ET is controlled mainly by atmospheric factors. This has led to the postulate that under such conditions there is no significant difference among crops in their water uptake rates. But potential ET as initially defined by Thornthwaite (1948) and Penman (1956) refers to a short green-crop of uniform height never short of water, completely covering the ground on a sufficiently large area to prevent any advection effect. Such conditions are seldom met in natural cropped lands because of various reasons, resulting therefore in a need for measuring actual ET. Furthermore, the variability of rainfall from year to year coupled with the low water holding capacity of sandy soils are underlying factors in the recent expansion of irrigation in the Southeastern United States. But the vulnerability of the groundwater to agrochemical pollution added to the operating cost of irrigation systems has led several researchers, including Hammond (1981a), Hammond and Bennett (1988), Camp and Campbell (1988) to re-evaluate water management strategies for the region. A suitable compromise needs to be found through irrigation timing and amounts in order to satisfy the evapotranspiration demand of crops at all stages of their development, while minimizing the loss of water by deep percolation and runoff. On the other hand, crop water stress induced by withholding or delaying water application allows the

simulation of various environmental conditions necessary for the description of crop-water relations on a broader range for prediction purposes.

Physics of Evaporating Surfaces

Evapotranspiration is an energy as well as a mass flow process. It takes about 580 calories to convert one gram of liquid water into water vapor at a temperature of 30^0 C (Penman et al., 1967; Jones et al., 1984). The energy at the surface of the earth can be partitioned into energy inflows and energy outflows as follows:

$$R_s\,(1\text{-}r) - R_B = ET + H + G + P \qquad [28]$$

where R_s is the incoming short-wave solar radiation, r the albedo of the evaporating surface, R_B the net long-wave radiation from surface to sky, ET the latent heat flux (used to evaporate water without raising the temperature of the evaporating surface), H the sensible heat flux, G the soil heat flux, and P the energy used for photosynthesis (<5% of total energy expenditure). All the above components are usually expressed in energy flux density units (watts/m^2 or cal/cm^2.min) which can be converted into equivalent depths of water evaporated.

The relative importance of each component on the right hand side of Eq. [28] depends on three groups of factors (Penman et al., 1967; Gates and Hanks 1967; Ekern et al., 1967; Ritchie et al., 1972; Doorenbos and Pruitt, 1977; Stewart, 1984; Monteith, 1985):

(i) atmospheric factors, namely the incoming energy, air turbulence, relative humidity (or vapor pressure deficit) and temperature;

(ii) plant factors such as the mean stomatal resistance, leaf area, canopy structure, roughness and color, plant height, density, row spacing and orientation, stage of growth, rooting depth and root characteristics;

(iii) soil factors, i.e., soil type and color, and availability of soil water.

Influence of Crop Factors on ET

There have been conflicting results on the effects of various plant factors on ET rates. Briggs and Shantz (1913) reported measurable differences in water requirements (transpiration rate) among crop species and even varieties within the same species. But in a later paper the same authors (Briggs and Shantz, 1916) refuted the idea that wheat and similar crops increase their water demand suddenly at or just before the time of heading. They suggested that the transpiration rate increases uniformly during that period. Penman (1956) made two broad generalizations when he stated that (1) for complete crop covers of different plants having about the same color, thus the same albedo, the potential transpiration rate was the same and (2) was determined by the prevailing weather, irrespective of plant or soil types. But it would be worth pointing out that Penman's contention sets its own restrictions.

Angus (1959) has discussed quite extensively the influence of crop characteristics on ET. According to him, the length of time the crop is in leaf and the percentage of ground cover may be the main effects of crop type on water use. But he further stated that there have been no reliable experiments to demonstrate any marked difference in the potential ET rates of various plants. Nevertheless, he gave some reasons why different crops may not be expected to have the same water-use rate. Such reasons include (i) different reflection coefficients, (ii) different insulating

properties, (iii) different influences on turbulence (due to differing canopy structures) and (iv) different stomatal closure patterns.

On the local scale, the input radiation in a given area is supposedly independent of the underlying surface (Stewart, 1984) (except when advection effects become non-negligible); but the outgoing components of the radiation are influenced by the characteristics of the evaporating surface. The reflected short-wave radiation depends on the albedo of the surface which is about 13-30% for most agricultural plants (Gates and Hanks; 1967; Jones et al., 1984), about 10% for forests (Stewart, 1984) and 15-60% for bare soils depending on organic matter and water contents (Monteith, 1973; Jones et al., 1984; Stewart, 1984). Stewart (1984) postulated that the efficiency of removal of water vapor from the evaporating surface was the second most important factor governing the rate of ET when soil water was not limiting. He showed that the rate of transfer of water vapor increases rapidly as the surface roughness increases. This means that, all other conditions being equal, tall vegetations like trees and even medium plants like corn and sorghum would supposedly exhibit a greater efficiency in transferring water vapor, thus a greater rate of ET than shorter crops like peanut, or bare soils (Hatfield et al., 1983; Stewart, 1984). As a supporting evidence to his hypothesis, Stewart reported how a change from native forest vegetation to annual agricultural crops (wheat) in Western Australia resulted in the creation of a wetland because of a significant rise of the water table due to a decrease in evaporation. The effect of plant cover and the associated differential growth patterns are also important, mainly in row crops where the percentage of ground cover varies from 0% at planting to about 100% by the end of the growing season. The three main factors related to the degree of canopy cover may be (1) the differential reflectivity of bare soil versus

crop canopy; (2) the differential and changing water loss rates from bare soil (evaporation) and from crop (transpiration) depending on wetting and drying cycles; and (3) the change in the height and canopy structure of the crop as it grows. Gates and Hanks (1967), Tanner and Jury (1976), and Passioura (1983), citing many investigators, reported that for most crops ET rates have been shown to increase with the per cent cover up to about 50% ground cover or leaf area index (LAI) of 2.0 or greater. The same authors also suggested that complete full canopy ground cover is not necessary to attain maximum ET rates for most crops. Ritchie (1972), and Tanner and Jury (1976) proposed empirical models using LAI as input data to measure potential evaporation and transpiration separately, from row crops of sorghum and potato with incomplete cover, respectively.

The importance of rooting depth has also been emphasized. The extent and depth of rooting determine the volume of soil from which plants can extract water. Evidently, ET is greater the more extensive and deep the rooting characteristics of the plant, provided soil water is limiting in the upper part of the profile. Rooting depth and extent would be expected to have much less influence on ET under adequate soil water status (Gates and Hanks, 1967; Passioura; 1983).

On a different perspective, the premise of equal potential ET rates for different crops, all other conditions being the same, may be advantageously investigated as a means to improve water-use efficiency through cropping patterns. Such improvements may come about through increased planting density or intercropping which would result in early full canopy ground cover, and consequently less water loss by direct evaporation from bare soil.

Measuring Actual ET in a Cropped Field

Many approaches have been devised to predict or measure ET ranging from empirical or semi-analytical formulas to a complete modeling of the soil-plant-atmosphere system.

Empirical methods

Penman's analytical model proposed in 1948 and improved since then by its author, and many others, has been used worldwide as the standard method for predicting potential evapotranspiration of the reference crop (i.e. usually a green short turf). Potential ET of a given crop is then calculated via an experimentally determined crop coefficient (Doorenbos and Pruitt, 1977; Tsakiris, 1988). The attractiveness of Penman's model results from the fact that it was derived from a sound mathematical analysis of the energy balance equation (Eq. [28]). The working Penman equation for predicting daily potential ET of a reference crop can be written as (Jones et al., 1984):

$$ET_p = (\Delta/\Delta+\gamma)[(1-r)R_s - \sigma\ T^4\ (0.56 - 0.08\ \sqrt{e_d})(1.42\ R_s/R_{so} - 0.42)]/\lambda$$
$$+ (\gamma/\Delta+\gamma)[0.263(e_a-e_d)(0.5 + 0.0062\ U_2)] \qquad [29]$$

where ETp is potential ET in mm/day;

$\Delta =$ slope of saturated vapor pressure curve of air, mb/°C;

$\gamma =$ psychrometric constant = 0.66 mb/°C;

$R_s =$ total incoming solar radiation, cal/cm^2.day;

$R_n =$ (1-r) R_s - R_B

$R_n =$ net radiation in cal/cm^2.day;

R_B = net outgoing thermal or long-wave radiation, cal/cm^2.day;

R_{so} = total cloudless sky radiation, cal/cm^2.day;

r = albedo = 0.23 for green vegetated surfaces;

σ = Stefan-Boltzmann constant = 11.71 x 10^{-8} cal/cm^2.day/^{o}K;

e_a = vapor pressure of air = $(e_{max} + e_{min})/2$, mbar;

e_d = vapor pressure at dewpoint temperature (Td), mbar

(For practical purposes Td ≈ Tmin)

T = average air temperature, ^{o}K

λ = latent heat of vaporization of water

= 59.59 - 0.055T cal/cm^2.mm or about 58 cal/cm^2.mm at 29^{o}C.

U_2 = wind speed at height of 2 meters in km/day.

Because of the many parameters and input data involved in Penman's equation, simpler and more empirical models have been proposed by several authors. One such model used extensively in French speaking countries is the Turc equation (Turc, 1961) which has been shown to give similar results as the Penman model in a subequatorial climate (Omoko, 1984). Its formulation is as follows:

$$ETp = K\ (R_s + 50)\ [t/(t + 15)][1 + (50 - HR)/70] \qquad [30]$$

where ETp is potential ET in mm for a given time period;

K = 0.013n where n is the number of days in the time period considered;

R_s = total incoming solar radiation, cal./cm^2.day;

t = average air temperature in ^{o}C;

HR = mean relative humidity of the air in per cent.

The term $(1 + \frac{50 - HR}{70})$ becomes negligible when HR ≥ 50%, which is the case

in Florida during the growing season.

Water depletion method

The soil water depletion method for measuring ET is based on the soil water balance equation

$$P + I = ET\ (Z,\theta,t) + R + D\ (Z,\theta,t) + \Delta S + \Delta V \qquad [31]$$

with ET = E + T,

where P is precipitation which occurred during a time period, I the irrigation amount, ET the amount of water lost to the atmosphere by evaporation (E) and transpiration (T), R the surface runoff out of the area ($R > 0$) or to the area ($R < 0$), D the downward drainage out of the root zone ($D > 0$) or upward capillary rise to the root zone ($D < 0$), ΔS the change in soil water storage within the root zone (positive or negative) and ΔV the change in plant water storage (positive or negative). All these quantities are usually expressed in terms of water volume per unit of land area, i.e. in units of depth.

The term ΔV is generally negligible compared to the other terms of the equation. The amount of runoff R can also be considered negligible in level, well-drained sandy soils because of their high water infiltration rates. ET (Z,θ,t) corresponds to the root water uptake term of Eq. [4]; P, I and Δs can be measured quite easily. Solving Eq. [31] then requires an independent determination of either ET or D.

Hillel (1977) and Molz (1981) presented extensive reviews of water transport models in the soil-plant-atmosphere system. The major drawback of mechanistic approaches for determining the water uptake term ET comes from the technical

difficulties involved in getting reliable input data required by the models. Most root water extraction functions assume that the uptake of water is uniform throughout the entire length of the root system. However, it has been shown (Newman, 1974; Passioura, 1980 and 1983) that root elements or portions of individual roots may not be equally effective in water absorption and that their differential efficiency may vary with root age and associated degree of suberization, and also with soil water status. To a good approximation, the rate of uptake of water from a given volume of soil is proportional to the rooting density L (cm root/cm^3 soil). But considerable uncertainty exists about the fraction of the total root length effective in water uptake (Greacen et al., 1976). Passioura (1980), working on wheat seedlings growing in a medium-textured soil in the laboratory reported an effective L of about one-third of the actual root length density.

Until more accurate methods of assessing root geometry and functioning in field crops are devised, the need for simpler approaches for estimating the sink term in the soil water flow equation (Eq. [4]) will remain. An often observed pattern of water uptake by roots is such that the top layer tends to be depleted first, and the zone of maximum extraction moves gradually into deeper layers as the upper soil becomes drier (Hillel, 1977; Passioura, 1983). By predicting water flux below the active rhizosphere using the hydrodynamic characteristics of the soil, one can estimate the drainage component D of the water budget equation (Eq. [31]) which can then be solved for ET (Rose and Stern, 1967; Larue et al., 1968; van Bavel et al., 1968a and 1968b; Hillel, 1972; Luchiari, Jr., 1987).

Because of the inherent spatial variability of soil hydraulic properties, the water depletion method has been used more extensively in lysimetry than in cropped lands.

Pruitt and Lourence (1985) among others have reviewed the inherent problems associated with lysimeter studies ranging from their extreme sensitivity to wind speed to their failure to represent the natural soil profile as well as crop growth and ET conditions in a large field. What the field method loses in resolution is certainly gained in validity.

Materials and Methods

In order to evaluate daily water use and the differential water uptake patterns of corn (Zea mays L.), sorghum (Sorghum bicolor (L.) Moench) and peanut (Arachis hypogaea L.) crops, two experiments were conducted in 1986 and 1987 in Unit 2 of the Irrigation Research and Education Park in Gainesville. The soil is classified as a Millhopper fine sand, a member of the loamy, hyperthermic family of Grossarenic Paleudults (Calhoun et al., 1974). The depth to the underlying argillic horizon varies between 100 and 190 cm.

Corn, grain sorghum and peanut are all warm-season crops. The maize hybrid chosen (Pioneer Brand 3165) is known to be more water stress tolerant than many other cultivars grown in Florida (Lorens, 1984; Loggale, 1985; Lorens et al., 1987a and 1987b). Sorghum is often grown on marginal soils in areas where rainfall is insufficient and temperatures are too high for satisfactory corn production. It is not usually irrigated. Sorghum crop offers proven versatility, hardiness, dependability, and stability of yield under very adverse conditions (House, 1978). It is sometimes grown in association with a variety of crops (cowpea, pigeon pea, peanut, beans). Peanut crop is well adapted to well-drained fine to medium-textured soils and a growing season with a minimum of 100 days in the optimum temperature range. Irrigation on peanut

has become common practice in the Southeastern States of the US, but improper irrigation scheduling may result in little or no yield response, or even in reduced yield (Henning et al., 1982).

Field Procedures

The two experiments were carried out in the same area during the Summer of 1986 and Spring and Summer of 1987.

1986 experiment

Only grain sorghum, Northrup King Savanna 5 hybrid, and peanut, Florunner cultivar were planted. Both crops were planted on June 20, 1986.

Planting pattern. Sole sorghum was seeded in 30 cm rows with a 13.3 cm intra-row spacing, resulting in a density of about 250 000 plants/ha after thinning. Sole peanut was planted in 30 cm rows with 18.5 cm between plants for a total density of 180 000 plants/ha. In intercropping subplots, both crops were planted in 60 cm alternate rows with 6.6 cm and 9.25 cm intra-row spacing for sorghum and peanut respectively resulting in a total population of 250 000 p/ha for sorghum after thinning (100% of sole sorghum density on 50% of land area) and 180 000 p/ha for peanut, (100% of sole peanut density seeded on 50% of the land area). Before planting, a 0-6-25 (N-$P_2 0_5$-$K_2 0$) fertilizer containing 6.5% Mg, 0.75% Zn and 0.25% B was broadcast and incorporated on the plot area as base application at a rate of 454 kg/ha. Nemacur was broadcast on the plots three days after planting at a rate of 35 kg/ha. Two split applications of ammonium nitrate were banded along sorghum rows at a rate of 100 kg N/ha at 21 and 34 DAP, respectively, resulting in a total of 200 kg N/ha; 800 kg/ha of gypsum were broadcast on peanut at 31 DAP (one week after the beginning of flowering) as source of calcium to promote pod filling. Dipel, thuricide and lannate

were used successively when needed to control armyworms on sorghum. Bravo 500 was sprayed every other week from 42 DAP to control Cercospora leaf spot on peanut.

Experimental design. The layout was a randomized block split-plot design with three water managements as main treatments and three cropping systems as subtreatments in four replications. Each main plot was 14m x 14m in size, divided into four subplots planted to sorghum, peanut, sorghum-peanut intercropped and Phaseolus (which was not part of this study). The main treatments were

(1) WM1, optimum water management in which irrigation was applied to prevent any visible stress on either one of the crops. Irrigation was triggered whenever the soil water pressure at 15 and/or 30 cm depths was less than - 200 mb in sorghum subplots;

(2) WM2, irrigation applied after two days of visible stress (wilting) on sorghum or when the soil water pressure at 15 and/or 30 cm depths was lower than -500 mb;

(3) WM3, rainfed.

Rainfed plots were irrigated along with the two irrigated treatments on occasions from planting until 19 DAP to ensure proper crop establishment. Full canopy cover in treatments WM1 and WM2 was attained at about 30 and 37 DAP in sorghum and peanut respectively. Booting and heading stages on sorghum occurred between 42 (WM1) and 60 DAP (WM3). Sorghum and peanut were harvested after 102 and 134 days, respectively.

1987 experiment

Corn (Pioneer Brand 3165) was added to the two crops grown in 1986 and Florunner peanut was replaced by the newly released Southern Runner cultivar which is more indeterminate and leaf spot resistant (Gorbet et al., 1986). Moreover, planting pattern in intercropping was modified, with the objective of increasing the competitiveness of peanut crop.

Planting pattern. Sole sorghum was planted in 61 cm rows with a density of 256 000 p/ha after thinning. Sole peanut was seeded in 61 cm rows and 10 cm intra-row spacing resulting in a total population of 160 000 p/ha. Corn was planted in 61 cm rows at a density of 80 000 p/ha. In sorghum-peanut intercrop, two paired rows of sorghum 30 cm apart were alternated with two paired rows of peanut 45 cm apart; the distance between sorghum and peanut rows was 60 cm resulting in a density of 157 000 p/ha for sorghum (61.5% of sole sorghum density occupying about 46% of land area) and 102 000 p/ha for peanut (61.5% of sole peanut density sown on 54% of land area). The three crops were seeded on April 13 and 14, 1987.

Prior to planting the seedbed preparation involved plowing, incorporation of 0-10-20 (N-P_2O_5-K_2O) fertilizer containing 0.06% B, 0.06% Cu, 0.36% Fe, 0.15% Mn, and 0.014% Mo as top dressing at a rate of 830 kg/ha, and of Furadan at a rate of 43 kg/ha, and then disking. Ammonium nitrate was applied in band along maize and sorghum rows as side dressing in three split applications at 16, 36 and 56 DAP resulting in a total of 250 Kg N/ha; 900 kg/ha of gypsum were broadcast on peanut crop at 45 DAP as source of calcium to promote pod filling. All the crops were properly cared for against weed, pests and diseases during the growing season. Lasso was applied at a rate of 2.4 liter/ha as a pre-emergence herbicide for weed control in

corn and peanut. Weed control in sorghum was done by hand hoeing. A bi-weekly application of Lannate starting from 30 DAP was made to control armyworms and corn ear worms in maize and sorghum crops. Peanut received a bi-weekly application of Bravo 500 between 66 and 160 DAP, to prevent Cercospora leaf spot.

Experimental design. The layout was a randomized block split-plot design replicated four times. Main plots were four water treatments and subplots were four cropping systems (corn, sole sorghum, sole peanut, and sorghum-peanut intercropped). The main treatments were:

(1) WM1, optimum water management with irrigation applied to prevent any visible sign of water stress on any one of the three crops. Water application was based on corn water requirements and was triggered whenever the soil water pressure at 15 and/or 30 cm depths was lower than - 200 mb in corn subplots;

(2) WM2, irrigation after two days of wilting on sorghum or when the soil water pressure at 15 and/or 30 cm depths was less than - 500 mb in the sole sorghum subplots;

(3) WM3, irrigation after two days of wilting on peanut or when the soil water pressure at 15 and/or 30 cm depths was less than -500 mb in the sole peanut subplots; and

(4) WM4, rainfed, except when all treatments were irrigated for crop establishment. This required irrigation on 13 occasions up to 27 DAP.

Apparent full canopy cover in sole sorghum was attained by 47, 51, and 58 DAP, in WM1, WM2, and WM3, respectively. The corresponding dates were 62, 66, and 69 DAP in corn, and 78, 82, and 90 DAP in sole peanut. None of the rainfed plots attained full canopy cover in sole sorghum or corn, whereas peanut reached

complete ground cover by 100-120 DAP. All intercropping subplots reached full canopy later than either one of the sole crops in any given water management. All the crops were harvested at physiological maturity, 102 days (WM1), 107 days (WM2), 126 days (WM3 and WM4) for sorghum, 122 days for corn, 160 days for peanut. A second harvest was done at 203 days for peanut.

Harvest procedures. In sole crops, the harvest area consisted of 4 meters of row (0.5 to 4.5 m from the center of the plot) on the 3rd and 4th rows from the center line of each plot. In intercrop subplots, two paired rows of sorghum (or peanut) bordered on both sides by two paired rows of peanut (or sorghum) were harvested on a row length of 4 meters.

The total above-ground biomass of each crop was dried at 150°F (corn and sorghum) or 90°F (peanut) until constant weight. Peanut yield consisted of both above- and below- ground parts. Kernel yields were then adjusted to 15.5% (corn), 13% (sorghum), and 7% (peanut) gravimetric water contents.

Water Management

The strategy used in irrigation scheduling was to partly replenish the depleted soil profile within the root zone during periods of deficit rainfall (when rainfall was less than crop ET) in order to take full advantage of any unexpected precipitation. Irrigation water was applied early in the morning (6:00 a.m.) when the winds were calm, using a solid-set impact sprinkler system. Quarter circle sprinklers located at the corners of 14 m x 14 m plots gave a full two-sprinkler overlap along the plot edges and a four-sprinkler overlap in the center. Each sprinkler delivered 6.56 gallons of water per minute when the pressure on the manometer of the control valve was set at

60-65 p.s.i. This would result in an application rate of 2.54 cm/hr when evenly distributed on the plot area. But the overlapping of the four sprinklings in the central part of the plot results in an uneven water distribution. In order to quantify the spatial variability of irrigation water application, 25 pots were installed on top of standing pvc pipes and used as irrigation gauges in plot 19 in the center South of Unit 2. Table 5 gives a summary of data collected in 10 irrigation runs when the winds were absolutely calm. For practical purposes the plot area was divided into 4 concentric squares: 5.6 m x 5.6 m, 8.6.m x 8.6 m, 11.6 m x 11.6 m, and 14 m x 14 m. The average intensities of irrigation were 3.00 cm/hr (mean 1), 2.85 cm/hr (mean 2) and 2.67 cm/hr (mean 3) for the first three squares, respectively. The corresponding coefficients of uniformity (CU) were 97.21%, 91.25% and 85.53% respectively. For comparison, CU values of 80% or more are commonly considered acceptable by most irrigators. A map of isointensity lines of irrigation application is represented in figure 12. Only the central part of each plot (5.6 m x 5.6 m) was used for water budget measurements.

One neutron access tube (inserted down to the top of the argillic horizon) and a set of 5 tensiometers (15, 30, 45, 60 and 90 cm depths) were installed 15 cm off the 3rd or 4th row of corn, sole sorghum, sole peanut, intercrop sorghum (IS) and intercrop peanut (IP) in each plot of replicates 1(NW section of Unit 2) and 2 (SE section). Only tensiometers, at depths above, were installed in replicates 3 (NE) and 4 (SW).

Data Collection

Water content data were collected every other day between 10:00 and 16:00 using a neutron probe (see chapter 2). Tensiometers were read with a tensimeter

Table 5. Spatial distribution of irrigation rates determined from 10 irrigation runs on plot 19, Unit 2, IREP.

Distance (m) to center of plot S-N Direction	E-W Direction	Mean rate (cm/hr)	SE cm/hr	Uniformity coefficient (%)
0	0	3.12	0.115	.
2.8	-2.8	2.88	0.319	.
2.8	0	3.10	0.224	.
2.8	2.8	2.91	0.325	.
0	2.8	3.01	0.261	.
0	-2.8	3.02	0.263	.
-2.8	-2.8	2.91	0.320	.
-2.8	0	3.14	0.239	.
-2.8	2.8	2.92	0.336	.
Mean 1		3.00	0.252	97.21
4.3	-4.3	2.29	0.202	.
4.3	0	3.12	0.258	.
4.3	4.3	2.26	0.202	.
0	4.3	2.95	0.252	.
-4.3	4.3	2.28	0.212	.
-4.3	0	3.11	0.342	.
-4.3	-4.3	2.39	0.203	.
0	-4.3	2.96	0.243	.
Mean 2		2.85	0.229	91.25
5.8	-5.8	1.77	0.239	.
5.8	0	2.51	0.166	.
5.8	5.8	1.79	0.243	.
0	5.8	2.52	0.192	.
-5.8	5.8	1.94	0.313	.
-5.8	0	2.80	0.392	.
-5.8	-5.8	2.02	0.252	.
0	-5.8	2.51	0.205	.
Mean 3		2.67	0.207	85.53

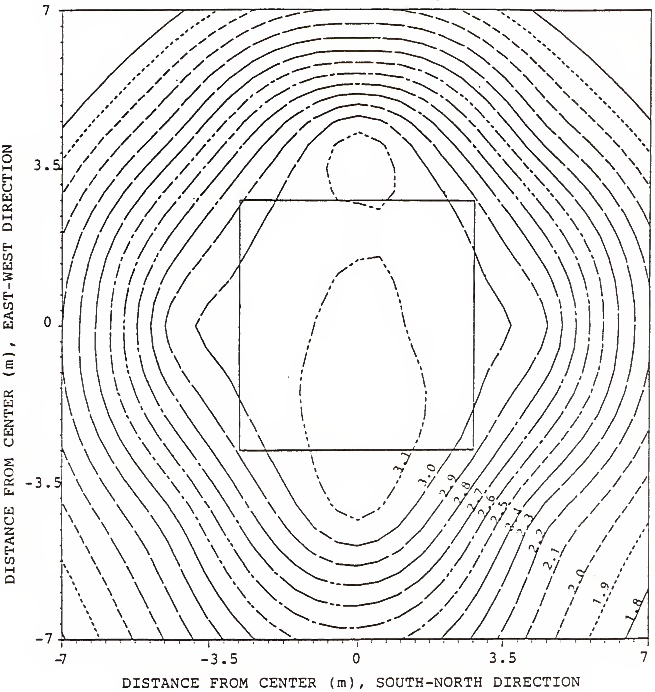


Fig. 12. Spatial distribution of irrigation intensity (cm/hr) in plot 19 (14m x 14m), Unit 2, IREP.

(cf.chapter 2) every day between 16:00 and 21:00 following the same sequence, so that data from each site were collected at about the same time of the day, except when it was raining. Malfunctioning tensiometers were serviced during the reading tour so that they would have 24 hours to re-equilibrate before the next reading.

Data Handling and Assumptions

Computations of water budgets were made from the data collected based on the following assumptions:

(1) surface runoff and internal horizontal water flow in the soil were negligible;

(2) hysteresis of the $K(\theta)$ function was not an important factor;

(3) the active root zone depth was limited to 90 cm and water flux at that lower boundary obeyed Darcy's law and was not directly influenced by root water uptake;

(4) the contribution of soil horizons below the 90 cm depth to the total water uptake was negligible;

(5) the soil profile down to the 90 cm depth was considered spatially homogeneous with regard to hydrodynamic properties.

Assumptions (3) and (4) can be justified by many observations. During the 1986 experiment, tensiometers were installed down to the 105 and 120 cm depths in several water-stressed plots and the pressure head data collected were in agreement with assumption (4). A recent mapping of the depth to the argillic horizon using ground penetrating radar has revealed that the said depth varies from less than 100 cm on the SE to 190 cm on the NW corners of Unit 2. But even above the top of the argillic horizon, randomly distributed clay lentils of various sizes can be found in the

profile. Such lentils become too frequent below the 90 cm depth in most of the SE and central parts of the unit. The potential error brought by such heterogeneities in the determination of soil hydraulic properties may be larger than that due to the aforementioned assumptions. The soil profile in Unit 2 consistently shows a plow pan at 40-60 cm depths which impedes root growth and eventually retards their exploration of deeper horizons. Figure 13 represents the root distribution measured at 82 DAP in the 1987 experiment by Nzeza (1988). The graph shows root length density values averaged over water managements 2, 3 and 4 which resulted in deeper rooting depths than the well irrigated treatment or the 1986 trial which had a more humid growing season.

The following hydraulic conductivity-water content regression function [K(θ)] determined empirically by fitting field data calculated using Darcy's law and Richards' equation was used to predict deep drainage D below the rhizosphere (chapter 2):

$$\text{Log } K(\theta)\big|_{z=90} = 8.555 \text{ Log } \theta + 8.759 \qquad [32]$$

with $R^2 = 0.897$

$$K(\theta)\big|_{Z=90} = 10^{(8.555 \text{ Log } \theta + 8.759)} \qquad [33]$$

$$D(\theta)\,\big|_{Z=90} = K(\theta)\ \partial H/\partial Z\big|_{Z=90} \qquad [34]$$

where $K(\theta)$ is the unsaturated hydraulic conductivity (cm/day) as a function of volumetric water content θ at 90 cm depth, H the hydraulic head in cm, Z the depth in cm, and $\partial H/\partial Z$ the hydraulic gradient at 90 cm depth.

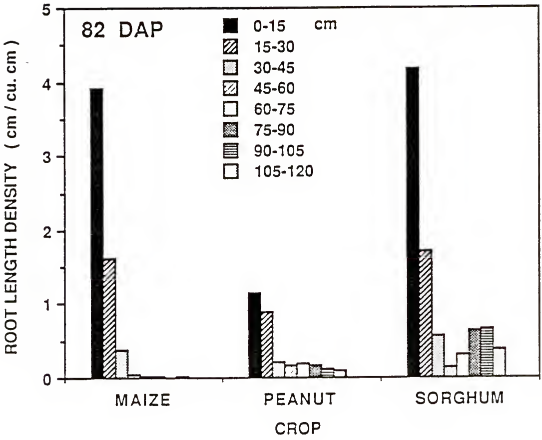


Fig. 13. Root length density (cm root/cm^3 soil) averaged over treatments 2, 3, and 4 at 82 DAP for corn, peanut, and grain sorghum in 1987 (Courtesy of Nzeza, 1988).

Water contents and hydraulic heads were averaged over each time period between 2 readings. Actual ET at each profile were then calculated using the water balance equation (Eq. [31]). Finally, the computed mean ET and D values for each water management were averaged over time periods of 7 to 11 days to reduce the daily fluctuations. All calculations and statistical analyses were done using Lotus spread sheet and the GLM procedures in SAS.

Results and Discussion

Soil Water Budget

1986 experiment

Sorghum crop. Figures 14a through 14c represent daily rainfall (solid vertical lines) and irrigation amounts (dashed vertical lines) as well as periodic soil water storage values in the root zone (0-90 cm depths). The horizontal dashed lines represent soil water depth in the root zone at a hypothetical uniform pressure head of - 200 cm (upper line) and - 15000 cm (lower line) corresponding to the critical level (CL) which would trigger irrigation in the well-watered treatment and the permanent wilting point (lower limit of soil water availability to plants, LL), respectively. All water in excess of the permanent wilting point was considered available to plants and could therefore be extracted by roots, as long as it remained within the 0-90 cm depth. Based on the aforementioned diagrams, none of the three treatments experienced damaging soil water deficits. The total water storage in the root zone dropped below the critical level only by the end of the growing season in the rainfed plots. But the arbitrary critical level (- 200 cm of pressure head) represents an ideal situation where root distribution and water extraction are uniform throughout the entire root zone profile. Considering that

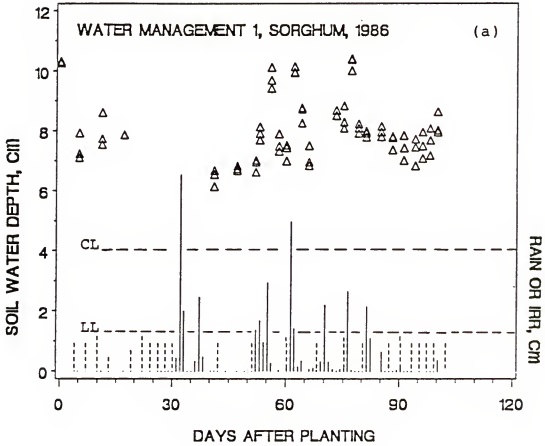


Fig. 14. Daily rainfall (vertical solid lines), irrigation (vertical broken lines), and soil water depths (triangles) in the rhizosphere (0-90 cm) of Northrup King Savanna 5 sorghum, IREP, 1986.

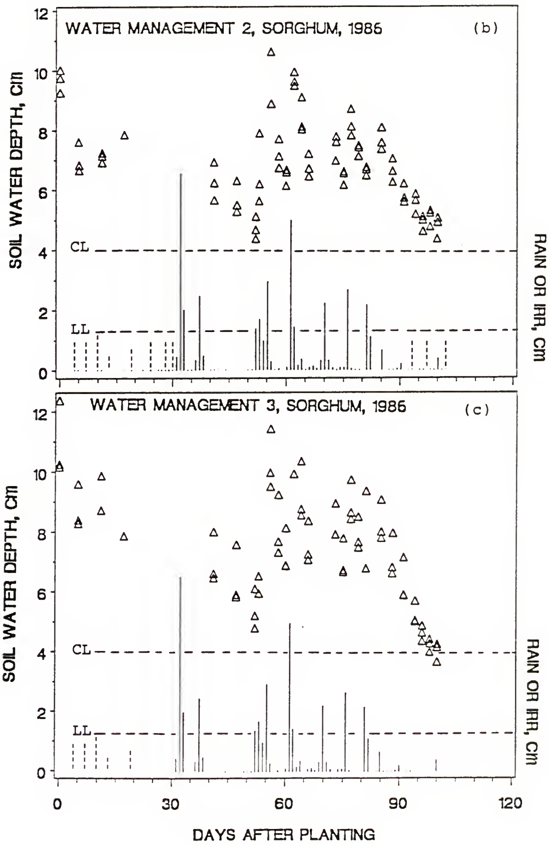


Fig. 14.- Continued

the zone of maximum water depletion was quite shallow (0 - 30 cm) as indicated by water content and water potential profiles (not included), sorghum crop in treatments 2 and 3 may have suffered some serious water stress around 50 DAP (booting stage) as well as at the end of the growing season. That situation is reflected on the computed periodic soil water balance data of Table 6 where actual evapotranspiration amounts in those water treatments were lower than in treatment 1. Numbers in parentheses indicate periodic irrigation amounts for each treatment whereas ΔS represents the algebraic change in water storage within the 0-90 cm depths. Table 6 also shows ratios between periodic water input (rainfall + irrigation) and potential ET (ETP) based on Penman's formula on one hand, and between actual and potential ET on the other hand. This last ratio corresponds to the crop coefficient and increased steadily from 0.25 early in the season to 1.05 at 56-62 DAP, then decreased. The last four lines of Table 6 represent the seasonal soil water budget where ETP, total water input, irrigation, change in water storage, drainage and ETA correspond to the algebraic sums of periodic values within each column for a given water management. A substantial amount of input water was lost by deep percolation in all water treatments (22.67 cm, 15.49 cm, and 11.25 cm in treatments 1, 2 and 3, respectively).

Peanut crop. Water input and soil water storage distributions during the growing season are represented in figures 15a through 15c. As for the sorghum crop, peanut may have experienced some water stress around 50 DAP and 100 DAP respectively in both the deficit irrigation (treatment 2) and rainfed (treatment 3) plots. Table 7 shows periodic soil water budgets calculated at arbitrary time intervals. Compared to sorghum, peanut crop exhibited slightly lower evapotranspiration rates early in the season and then reached its maximum water uptake by 85-98 DAP.

Table 6: Periodic water balance during the growing season of Northrup King Savanna 5 grain sorghum, Gainesville, 1986.

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	0-11 DAP (ETP=7.50 cm)					
1	2.1 (2.1)	-2.3	3.26	2.14	0.28	0.29
2	2.1 (2.1)	-3.08	3.39	2.48	0.28	0.33
3	2.1 (2.1)	-2.01	3.24	1.91	0.28	0.25
	11-17 DAP (ETP=3.65 cm)					
1	1.8 (1.8)	0.03	0.38	1.39	0.49	0.38
2	1.8 (1.8)	0.15	0.02	1.63	0.49	0.44
3	1.8 (1.8)	-0.01	0.3	1.51	0.49	0.41
	17-41 DAP (ETP=14.0 cm)					
1	19.46 (6.95)	-1.49	7.93	13.02	1.39	0.93
2	17.26 (4.75)	-1.65	5.4	13.51	1.23	0.97
3	13.26 (0.75)	-0.76	1.56	12.46	0.95	0.89
	41-47 DAP (ETP=2.73 cm)					
1	1.00 (1.00)	-1.81	0.001	2.81	0.37	1.03
2	0 (0)	-2.66	0.001	2.66	0	0.97
3	0 (0)	-2.15	0	2.15	0	0.79
	47-56 DAP (ETP=4.15 cm)					
1	8.38 (1.00)	3.56	0.6	4.22	2.02	1.02
2	7.38 (0)	3.01	0.08	4.29	1.78	1.03
3	7.38 (0)	3.26	0	4.12	1.78	0.99
	56-62 DAP (ETP=2.76 cm)					
1	7.69 (1.00)	0.33	4.49	2.87	2.78	1.04
2	6.69 (0)	-0.32	4.10	2.91	2.42	1.05
3	6.69 (0)	-0.38	4.24	2.83	2.42	1.03
	62-66 DAP (ETP=2.31 cm)					
1	0.60 (0)	-1.57	0.14	2.03	0.26	0.88
2	0.60 (0)	-1.55	0.06	2.09	0.26	0.90
3	0.60 (0)	-1.50	-0.02	2.12	0.26	0.92

Table 6--continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	66-73 DAP (ETP=3.08 cm)					
1	4.14 (1.00)	1.53	0.20	2.41	1.34	0.78
2	3.14 (0)	0.61	0.09	2.44	1.02	0.79
3	3.14 (0)	0.74	0.02	2.38	1.02	0.77
	73-79 DAP (ETP=2.84 cm)					
1	3.94 (1.00)	-0.12	1.79	2.27	1.39	0.80
2	2.94 (0)	-0.14	0.73	2.35	1.03	0.83
3	2.94 (0)	-0.23	0.86	2.31	1.03	0.81
	79-85 DAP (ETP=2.48 cm)					
1	4.98 (1.00)	0.21	2.71	2.06	2.01	0.83
2	3.98 (0)	0.88	1.09	2.01	1.60	0.81
3	3.98 (0)	1.01	0.89	2.08	1.60	0.84
	85-91 DAP (ETP=2.71 cm)					
1	2.25 (2.00)	-0.05	0.10	2.20	0.83	0.81
2	0.25 (0)	-1.89	0.04	2.10	0.09	0.77
3	0.25 (0)	-1.78	0.10	1.93	0.09	0.71
	91-98 DAP (ETP=3.21 cm)					
1	3.00 (3.00)	0.12	0.52	2.36	0.93	0.74
2	2.00 (2.00)	-0.53	0.23	2.30	0.62	0.72
3	0 (0)	-1.83	0.06	1.77	0	0.55
	98-102 DAP (ETP=1.65 cm)					
1	2.39 (2.00)	0.65	0.55	1.19	1.45	0.72
2	1.39 (1.00)	-0.09	0.26	1.22	0.84	0.74
3	0.39 (0)	-0.33	0	0.72	0.24	0.44
	0-102 DAP (ETP=53.07 cm)					
1	61.73 (23.85)	-0.91	22.67	40.97	1.16	0.77
2	49.53 (11.65)	-7.26	15.49	41.99	0.93	0.79
3	42.53 (4.65)	5.97	11.25	38.29	0.80	0.72

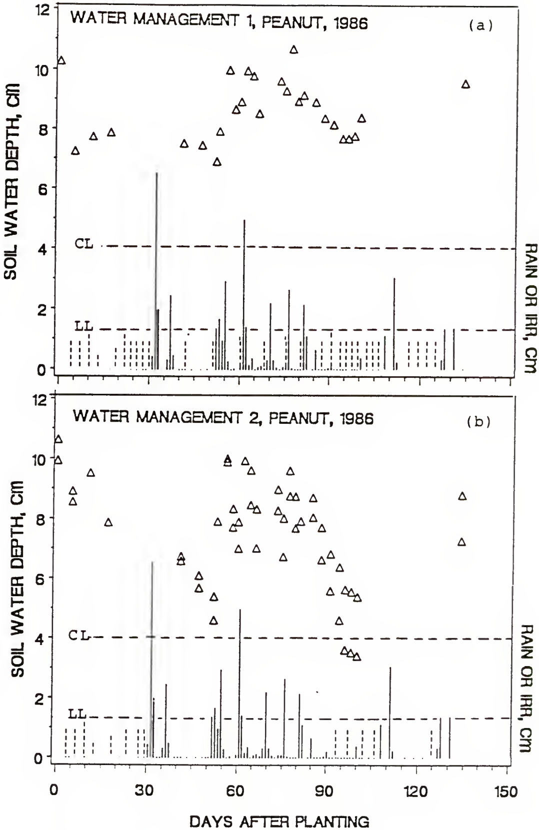


Fig. 15. Daily rainfall (vertical solid lines), irrigation (vertical broken lines), and soil water depths (triangles) in the rhizosphere (0-90 cm) of Florunner peanut, IREP, 1986.

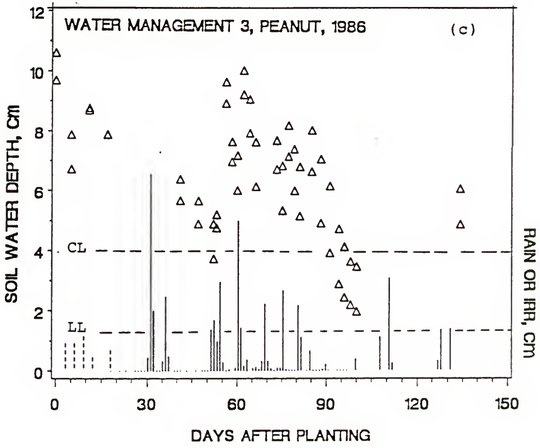


Fig. 15.- Continued

Table 7: Periodic water balance during the growing season of Florunner peanut, Gainesville, 1986.

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	0-11 DAP (ETP=7.50 cm)					
1	2.1 (2.1)	-2.08	3.55	1.91	0.28	0.25
2	2.1 (2.1)	-1.41	3.41	1.85	0.28	0.25
3	2.1 (2.1)	-1.33	3.23	1.81	0.28	0.24
	11-17 DAP (ETP=3.65 cm)					
1	1.8 (1.8)	0.18	0.43	1.19	0.49	0.33
2	1.8 (1.8)	-1.51	2.10	1.21	0.49	0.33
3	1.8 (1.8)	-1.06	1.68	1.18	0.49	0.32
	17-41 DAP (ETP=14.0 cm)					
1	19.46 (6.95)	-0.21	10.44	9.23	1.39	0.66
2	17.26 (4.75)	-1.42	9.22	9.46	1.23	0.68
3	13.26 (0.75)	-1.98	6.25	8.99	0.95	0.64
	41-47 DAP (ETP=2.73 cm)					
1	1.00 (1.00)	-1.13	0.02	2.13	0.37	0.78
2	0 (0)	-2.08	0.001	2.08	0	0.76
3	0 (0)	-2.18	0	2.18	0	0.80
	47-56 DAP (ETP=4.15 cm)					
1	8.38 (1.00)	3.41	1.43	3.54	2.02	0.85
2	7.38 (0)	3.32	0.59	3.47	1.78	0.84
3	7.38 (0)	3.17	0.59	3.62	1.78	0.87
	56-62 DAP (ETP=2.76 cm)					
1	7.69 (1.00)	1.10	3.99	2.60	2.78	0.94
2	6.69 (0)	0.94	3.19	2.56	2.42	0.93
3	6.69 (0)	1.02	3.06	2.61	2.42	0.95
	62-66 DAP (ETP=2.31 cm)					
1	0.60 (0)	-1.54	0.17	1.97	0.26	0.85
2	0.60 (0)	-2.12	0.73	1.99	0.26	0.86
3	0.60 (0)	-2.21	0.51	2.30	0.26	0.99

Table 7--continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	66-73 DAP (ETP=3.08 cm)					
1	4.14 (1.00)	1.12	0.25	2.77	1.34	0.90
2	3.14 (0)	0.09	0.49	2.56	1.02	0.83
3	3.14 (0)	0.18	0.35	2.61	1.02	0.85
	73-79 DAP (ETP=2.84 cm)					
1	3.94 (1.00)	-0.59	2.06	2.47	1.39	0.87
2	2.94 (0)	-0.51	0.69	2.76	1.03	0.97
3	2.94 (0)	-0.56	0.62	2.88	1.03	1.01
	79-85 DAP (ETP=2.48 cm)					
1	4.98 (1.00)	0.11	2.59	2.28	2.01	0.92
2	3.98 (0)	0.08	1.70	2.20	1.60	0.89
3	3.98 (0)	0.09	1.86	2.03	1.60	0.82
	85-91 DAP (ETP=2.71 cm)					
1	2.25 (2.00)	-0.56	0.02	2.79	0.83	1.03
2	0.25 (0)	-2.06	-0.36	2.67	0.09	0.99
3	0.25 (0)	-1.89	-0.40	2.54	0.09	0.94
	91-98 DAP (ETP=3.21 cm)					
1	3.00 (3.00)	-0.21	0.11	3.10	0.93	0.97
2	2.00 (2.00)	-1.54	0.19	3.35	0.62	1.04
3	0 (0)	-1.93	-0.10	2.03	0	0.63
	98-102 DAP (ETP=1.65 cm)					
1	2.39 (2.00)	0.56	0.37	1.46	1.45	0.88
2	1.39 (1.00)	-0.03	0	1.42	0.84	0.86
3	0.39 (0)	-0.11	-0.07	0.57	0.24	0.34
	102-134 DAP (ETP=8.98 cm)					
1	14.6 (7.00)	4.78	3.83	5.99	1.63	0.67
2	9.6 (2.00)	4.12	0.26	5.22	1.07	0.58
3	7.6 (0)	2.49	0	5.11	0.85	0.57

Table 7 -- continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	0-134 DAP (ETP=62.05 cm)					
1	76.33 (30.85)	4.94	29.26	43.43	1.23	0.70
2	59.13 (13.65)	-4.13	22.21	42.80	0.95	0.69
3	50.13 (4.65)	-6.30	17.58	40.46	0.81	0.65

1987 experiment

Corn crop. Daily rainfall, irrigation and soil water storage within the 0-90 cm depths for replicates 1 and 2 are represented in figures 16a through 16d for the four water treatments. Daily soil-water pressure head distributions within the root zone of corn crop in replicate 1 are illustrated in figures 17a through 17d for the 4 water managements. The same diagrams for the second replicate are given in Appendix C. All other conditions being equal, soil profiles in replicate 1 (NW quarter of Unit 2) systematically experienced drier conditions than in the other parts of the Unit, probably because of the deeper depth to the argillic horizon which induces higher drainage capabilities. Conversely, replicate 2 (SE quarter) exhibited the wettest soil conditions. Water depths in the rhizosphere never dropped below the critical level in well-irrigated plots (water management 1). Nevertheless, corn crop may have suffered minor afternoon water stresses around 60 and 80 DAP in replicate 1 because of high ET rates which could not be entirely compensated by root uptake. Such water stresses are common during hot afternoons, partly because of the uneven root distribution and root water uptake with depth as indicated earlier. The other three replicates did not show such low soil water potential or water content values, probably because of the shallower depth to the argillic horizon.

Severe soil water deficits (increasing from WM2 to 4) were observed in the profile in all other water treatments at about 45-72 DAP (silking, tasseling and pollination stages) 82 DAP and 95 DAP respectively, due to insufficient replenishment of depleted soil water in the root zone. Between two rainfall or irrigation events, soil water extraction by roots was maximum in the top layer (0-15 cm), then the depleted zone moved gradually downward as illustrated by the tensiometer readings (figures 17a

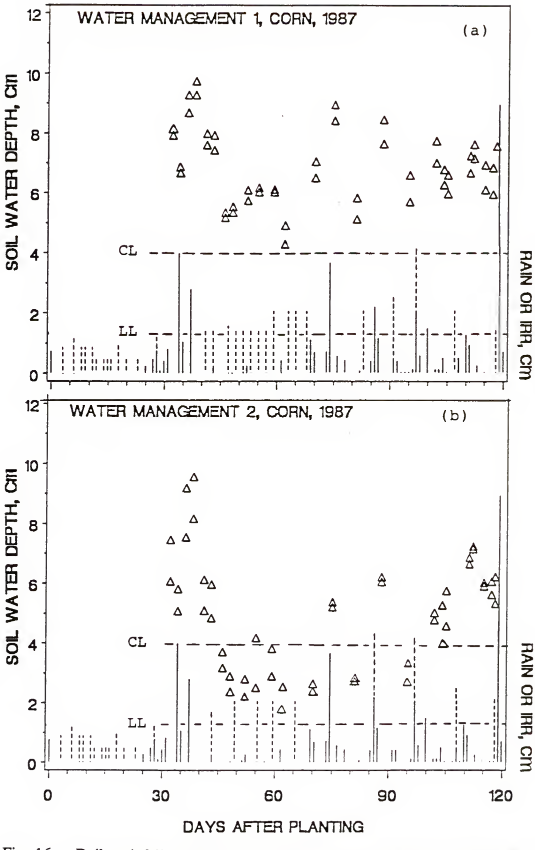


Fig. 16. Daily rainfall (vertical solid lines), irrigation (vertical broken lines), and soil water depths (triangles) in the rhizosphere (0-90 cm) of Pioneer 3165 corn, IREP, 1987.

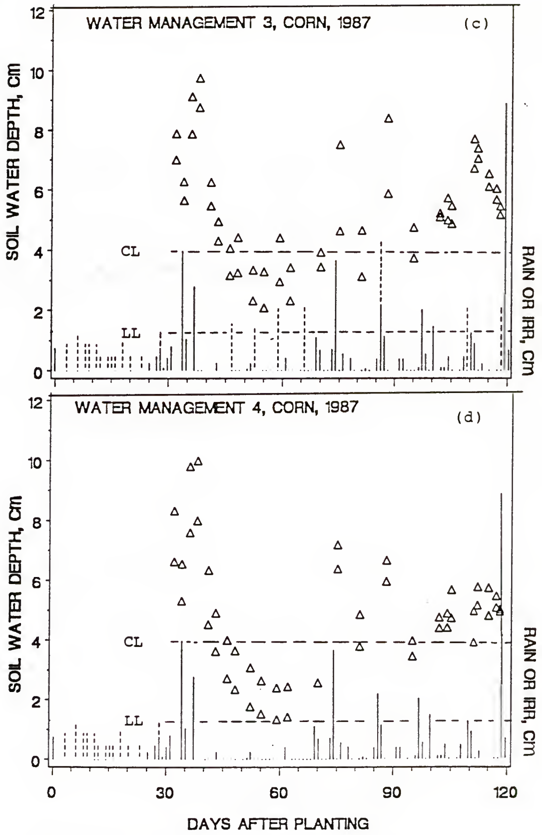


Fig. 16.- Continued

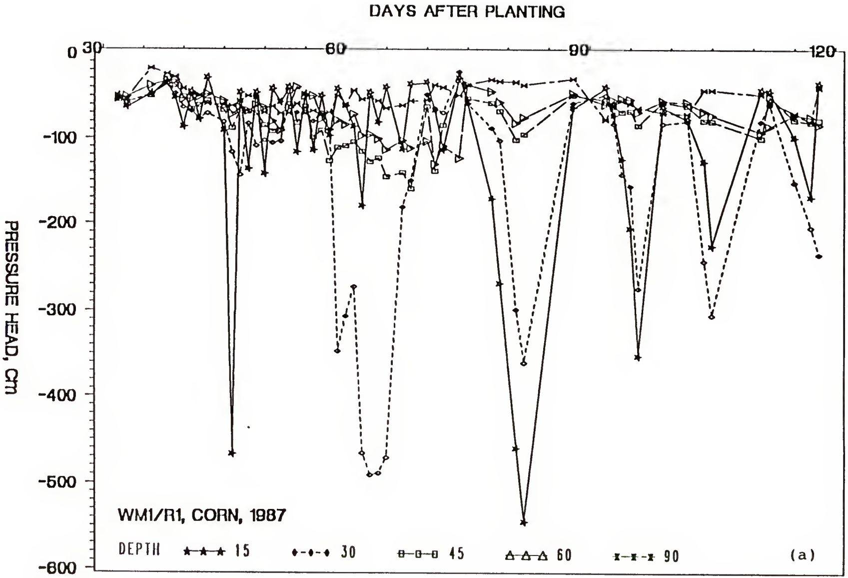


Fig. 17. Daily pressure heads in the root zone of Pioneer 3165 corn, IREP, 1987. WM1 stands for water management 1 whereas R1 stands for replicate 1.

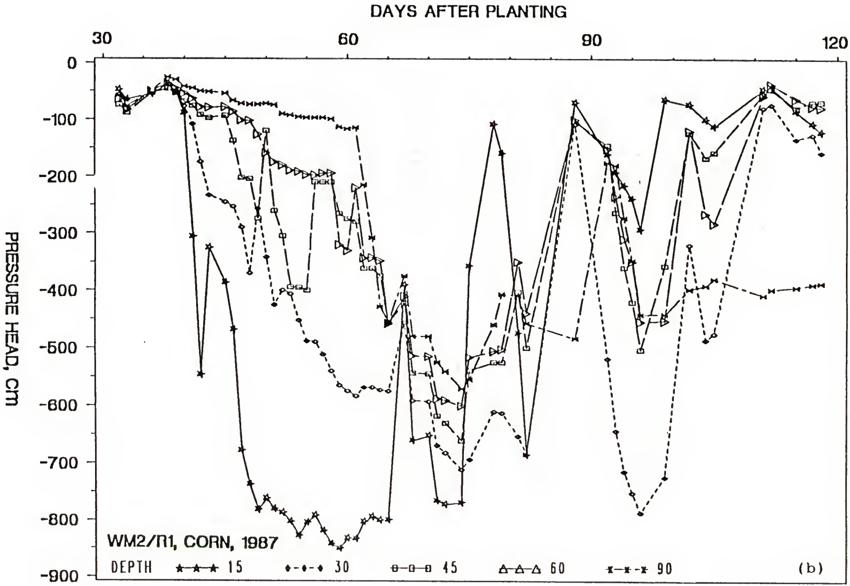
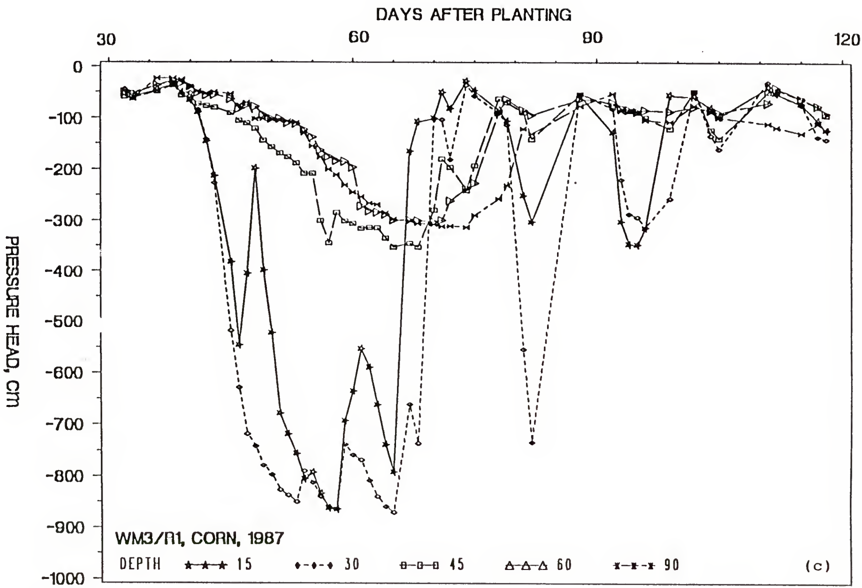


Fig. 17.- Continued



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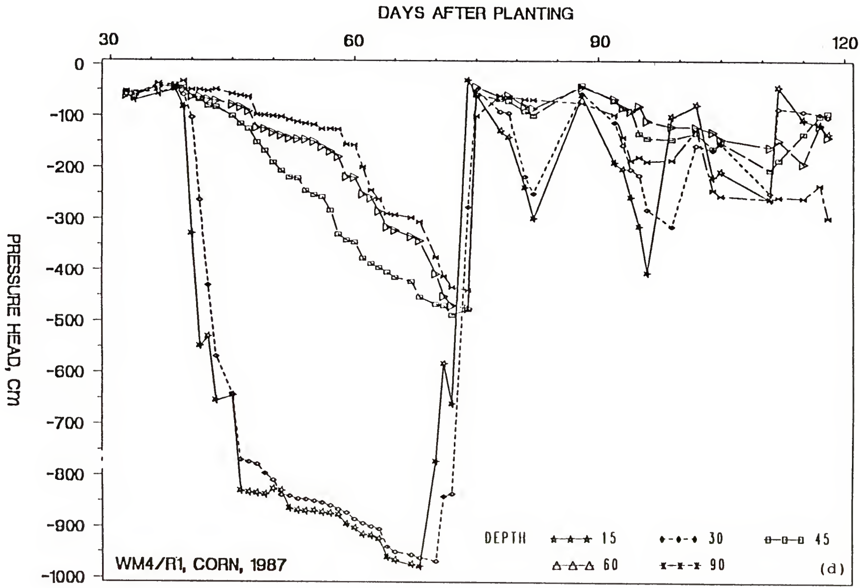


Fig. 17.- Continued

through d). Consequently, fluctuations in daily soil water status within the 0 to 90 cm depths decreased systematically with depth for any given water management.

Table 8 represents periodic soil water balance values computed at arbitrary time intervals during the growing season in corn crop. Crop coefficient (ETA/ETP) increased steadily from about 0.43 at initial growth stage to 1.4 at 52-59 DAP (mid-season crop development) in well-watered plots. The highest ET rates coincided with terminal vegetative development, silking and tasseling stages of the crop on one hand, and hot and dry weather conditions on the other hand (52-70 DAP). The confounding effects of growth stage and weather make it difficult to unambiguously give a scientifically sound interpretation to those high actual ET rates. Nevertheless, contributing factors include the relatively small plot size, the canopy structure and roughness of a fully-grown maize, and associated advective effects. In addition, a possible under estimation of the drainage component would have contributed to these inflated ET rates.

Sorghum crop. Daily rainfall, irrigation and soil water depths within the 0-90 cm depth for replicates 1 and 2 are represented in figures 18a through 18h. Figures 19a through 19d represent daily matric potentials at 15, 30, 45, 60 and 90 cm depths in replicate 1 of sorghum subplots for the four water managements. The second replicate, which includes also intercropping sorghum is given in Appendix C. The same symbolism was used as in figures 16 and 17, respectively. Early in the season, sorghum crop exhibited slightly higher soil water depletion rates than maize crop in the same treatments. That trend was then reversed by 52 DAP. On the other hand, water uptake in intercropping sorghum was slightly higher than in sole crop. Both

Table 8: Periodic water balance during the growing season of Pioneer 3165 Corn, Gainesville, 1987.

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	0-32 DAP (ETP=16.82 cm)					
1	13.54 (9.95)	3.10	3.25	7.18	0.8	0.43
2	13.54 (9.95)	2.98	3	8	0.8	0.48
3	13.54 (9.95)	3.07	3	7.39	0.8	0.44
4	13.54 (9.95)	3.16	3.04	6.98	0.8	0.42
	32-38 DAP (ETP=3.17 cm)					
1	7.98 (0)	1.58	3.66	2.74	2.52	0.86
2	7.98 (0)	2.10	3.23	2.65	2.52	0.84
3	7.98 (0)	1.80	3.48	2.70	2.52	0.85
4	7.98 (0)	1.52	3.78	2.67	2.52	0.84
	38-46 DAP (ETP=4.41 cm)					
1	3.25 (3.0)	-4.24	3.05	4.44	0.74	1.01
2	1.75 (1.5)	-5.11	2.28	4.58	0.40	1.04
3	0.25 (0)	-5.64	2.15	3.74	0.06	0.85
4	0.25 (0)	-5.63	2.16	3.72	0.06	0.84
	46-52 DAP (ETP=3.29 cm)					
1	4.89 (4.6)	0.66	0.70	3.53	1.49	1.07
2	2.39 (2.1)	-0.93	0.06	3.26	0.73	0.99
3	1.88 (1.6)	-0.78	0.02	2.64	0.57	0.80
4	0.29 (0)	-0.94	0	1.23	0.09	0.37
	52-59 DAP (ETP=4.14 cm)					
1	6.60 (6.6)	0.65	0.15	5.80	1.59	1.40
2	4.20 (4.2)	0.58	0	3.62	1.01	0.87
3	3.60 (3.6)	0.62	0	2.98	0.87	0.72
4	0.00 (0)	-0.55	0	0.55	0	0.13
	59-70 DAP (ETP=5.99 cm)					
1	8.53 (6.3)	0.78	0.23	7.52	1.42	1.26
2	4.34 (2.1)	-0.83	0	5.17	0.72	0.86
3	4.48 (2.24)	0.01	0.01	4.47	0.75	0.75
4	2.24 (0)	0.70	0	1.54	0.37	0.26

Table 8--continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	70-81 DAP (ETP=5.85 cm)					
1	5.40 (0)	-1.28	0.07	6.61	0.92	1.13
2	5.40 (0)	0.32	0.01	5.07	0.92	0.87
3	5.40 (0)	0.20	0.05	5.15	0.92	0.88
4	5.40 (0)	1.75	0.01	3.64	0.92	0.62
	81-88 DAP (ETP=4.02 cm)					
1	5.93 (2.1)	1.72	0.14	4.07	1.48	1.01
2	5.93 (2.1)	2.27	0.11	3.55	1.48	0.88
3	5.93 (2.1)	2.64	0.08	3.21	1.48	0.80
4	3.84 (0)	1.33	0.06	2.45	0.96	0.61
	88-95 DAP (ETP=3.65 cm)					
1	2.86 (2.1)	-1.89	0.98	3.77	0.78	1.03
2	0.76 (0)	-3.12	0.07	3.81	0.21	1.04
3	0.76 (0)	-2.89	0.33	3.32	0.21	0.91
4	0.76 (0)	-2.59	0.05	3.30	0.21	0.90
	95-102 DAP (ETP=4.00cm)					
1	6.42 (2.1)	1.03	0.87	4.52	1.61	1.13
2	6.42 (2.1)	1.89	0.11	4.42	1.61	1.11
3	4.32 (0)	0.92	0.07	3.33	1.08	0.83
4	4.32 (0)	0.87	0.12	3.33	1.08	0.83
	102-105 DAP (ETP=1.69 cm)					
1	0.58 (0)	-1.18	0.10	1.66	0.34	0.98
2	0.58 (0)	-0.98	0	1.56	0.34	0.92
3	0.58 (0)	-0.72	0.01	1.29	0.34	0.76
4	0.58 (0)	0.38	0	0.20	0.34	0.12
	105-115 DAP (ETP=5.02 cm)					
1	5.00 (2.1)	0.23	0.42	4.35	1	0.87
2	5.00 (2.1)	0.56	0.01	4.43	1	0.88
3	5.00 (2.1)	1.14	0.02	3.84	1	0.76
4	2.90 (0)	0.07	0	2.83	0.58	0.56

Table 8 -- continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	115-122 DAP (ETP=3.43 cm)					
1	11.40 (1.5)	1.22	7.52	2.66	3.32	0.77
2	12.01 (2.1)	1.07	8.31	2.62	3.50	0.76
3	12.01 (2.1)	1.41	8.09	2.51	3.50	0.73
4	9.91 (0)	1.96	5.57	2.38	2.89	0.69
	0-122 DAP (ETP=65.49 cm)					
1	82.40(40.35)	2.38	21.14	58.85	1.26	0.90
2	70.30(28.25)	0.80	17.19	52.74	1.07	0.80
3	65.74(23.70)	1.78	17.31	46.57	1.00	0.71
4	52.00(9.95)	2.03	14.79	34.82	0.79	0.53

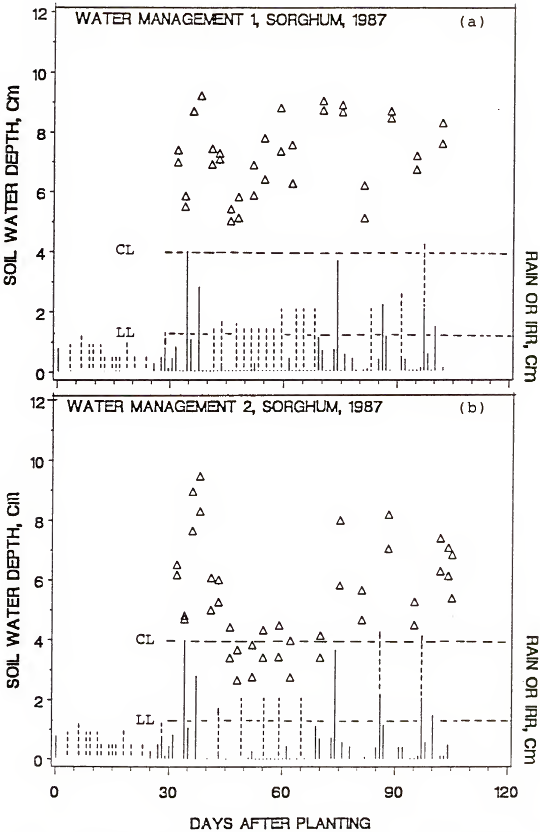


Fig. 18. Daily rainfall, irrigation, and soil water depths in the rhizosphere of Northrup King Savanna 5 sorghum, 1987, Gainesville.

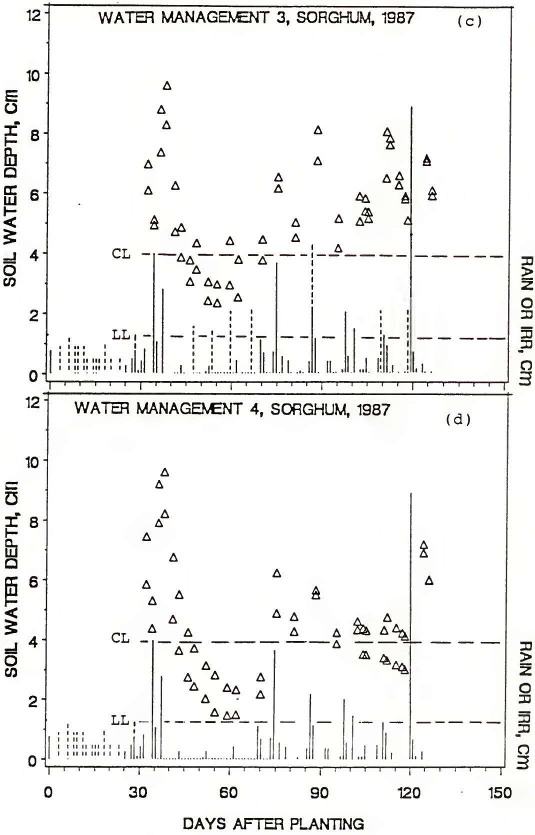


Fig. 18.- Continued

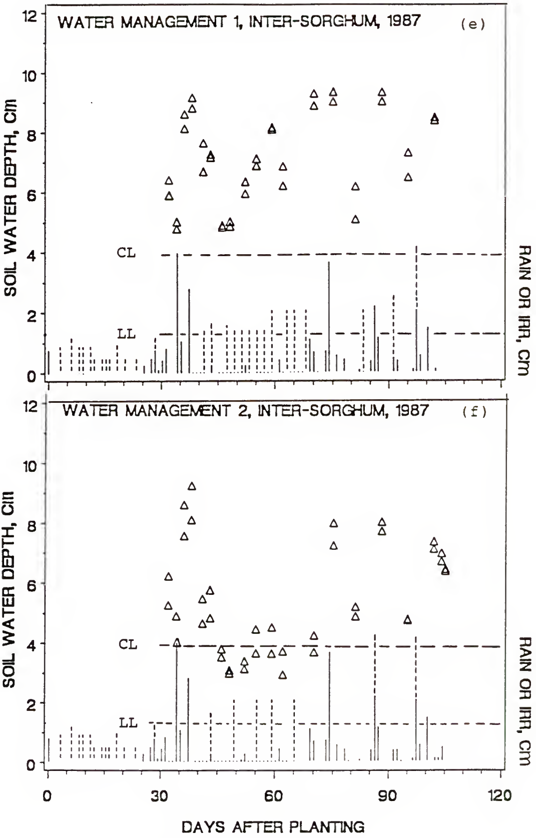


Fig. 18.- Continued

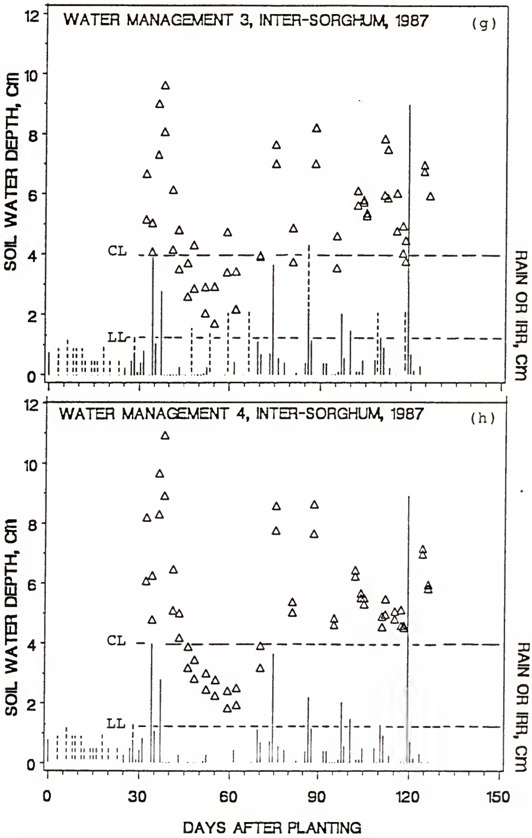


Fig. 18.- Continued

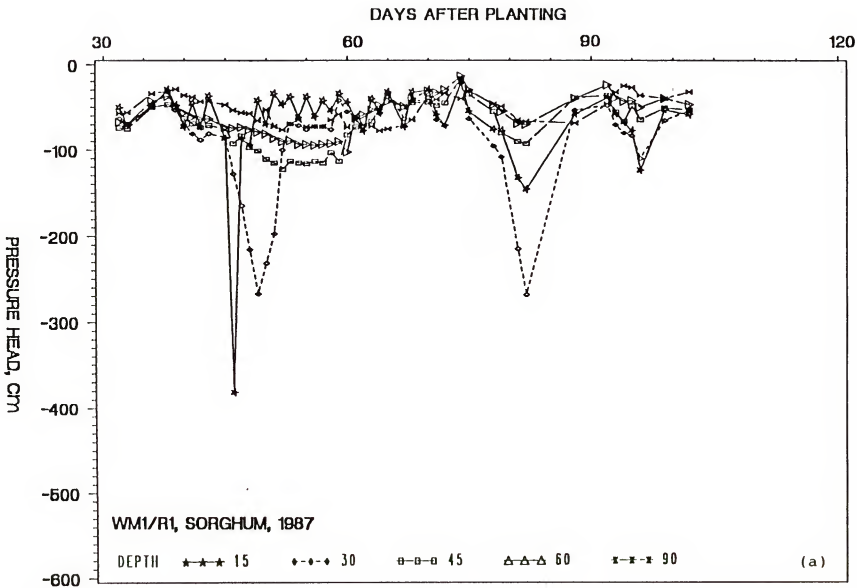


Fig. 19. Daily pressure heads in the root zone of Northrup King Savanna 5 sorghum crop in 1987.

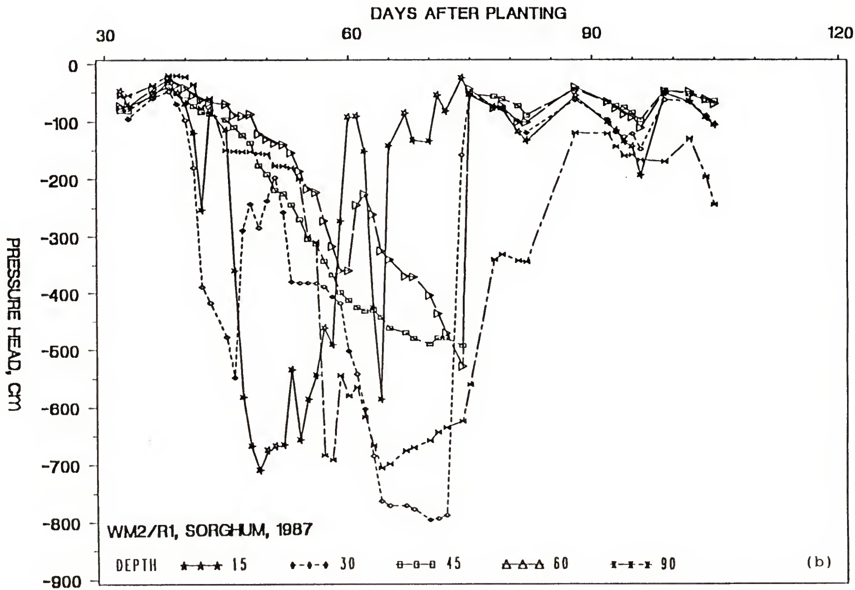


Fig. 19.- Continued

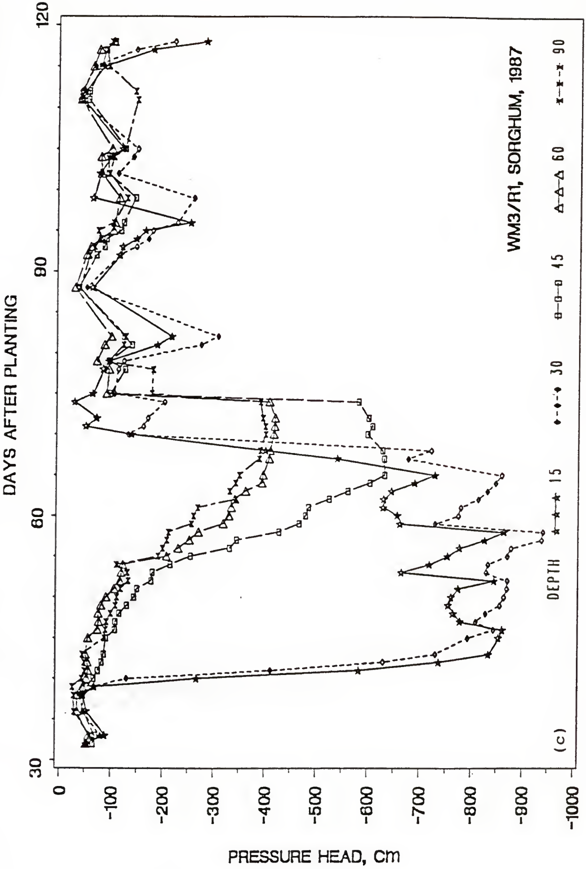


Fig. 19.- Continued

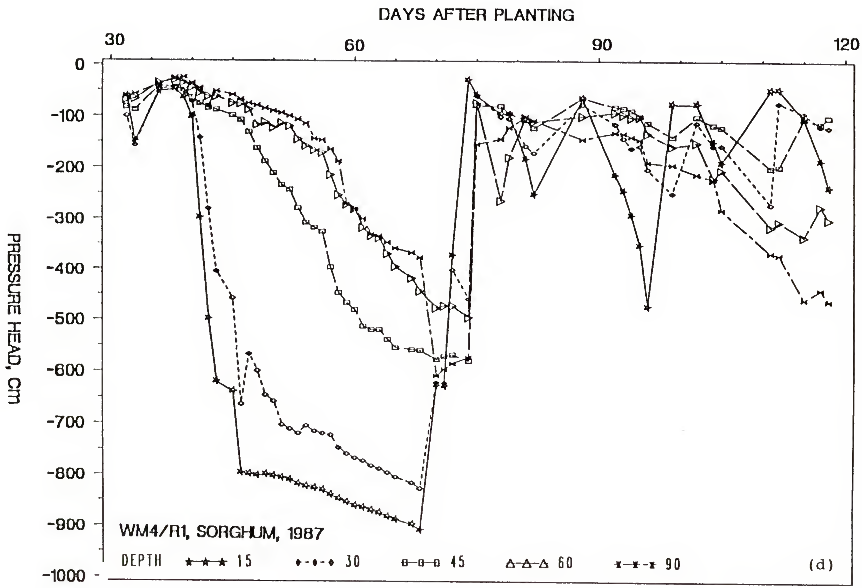


Fig. 19.- Continued

discrepancies in actual ET rates may be attributed to higher plant density of intercrop plots as compared to sole sorghum on one hand, and sole sorghum versus corn on the other hand.

Sorghum crop experienced some severe water stresses between 46 and 70 DAP (treatments 2, 3 and 4), at 95 DAP (treatments 3 and 4) and 95-115 DAP (treatment 4). The first drought cycle coincided with booting and heading stages and had a detrimental effect on reproductive growth of the crop in treatments 3 and 4. Most of the flowers aborted or resulted in very small panicles. Subsequent irrigation and rainfall events allowed some recovery in the sorghum crop which produced new tillers. As a consequence, harvest dates were delayed from 102 to 107 DAP in water management 2, and to 126 DAP in water managements 3 and 4. Table 9 represents periodic soil water budgets in sole sorghum subplots during the growing season. The ETA/ETP ratios for treatment 1 increased quite uniformly from 0.48 at 0-32 DAP to 1.14-1.18 at 38-52 DAP then started to decrease steadily until harvest after 102 days mostly because of leaf senescence. The last 5 lines in Table 9 give a summary of seasonal soil water balance from 0 to 102 DAP. Total evapotranspirations for intercropped sorghum were slightly higher than for sole sorghum (42.95 vs. 41.87 cm, 38.21 vs. 37.32 cm, 35.60 vs. 35.24 cm and 27.05 vs. 29.74 cm for WM1, 2, 3 and 4 respectively at 102 DAP), but the difference was not significant ($p = 0.05$).

Peanut crop. Rainfall and irrigation distributions as well as water storage within the root zone are illustrated in figures 20a through 20h. Daily soil water matric potentials for replicate 1 are represented in figures 21a through 21d. Diagrams for the second replicate, including intercropped peanut are given in Appendix C. Peanut subplots in treatment 1 (based on corn water requirements) exhibited relatively high

Table 9: Periodic water balance during the growing season of Northrup King Savanna 5 Grain Sorghum, Gainesville, 1987.

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	0-32 DAP (ETP=16.82 cm)					
1	13.54 (9.95)	1.44	2.40	8.02	0.80	0.48
2	13.54 (9.95)	1.56	3	7.01	0.80	0.42
3	13.54 (9.95)	1.09	3.04	7.04	0.80	0.42
4	13.54 (9.95)	1.34	2.90	7.30	0.80	0.43
	32-38 DAP (ETP=3.17 cm)					
1	7.98 (0)	2.01	2.64	3.33	2.52	1.05
2	7.98 (0)	2.54	2.15	3.29	2.52	1.04
3	7.98 (0)	2.41	2.45	3.12	2.52	0.98
4	7.98 (0)	2.26	2.67	3.05	2.52	0.96
	38-46 DAP (ETP=4.41 cm)					
1	3.25 (3.0)	-4.00	2.03	5.22	0.74	1.18
2	1.75 (1.5)	-4.97	1.94	4.78	0.40	1.08
3	0.25 (0)	-5.52	1.99	3.78	0.06	0.86
4	0.25 (0)	-5.17	1.95	3.47	0.06	0.79
	46-52 DAP (ETP=3.29 cm)					
1	4.89 (4.6)	1.38	-0.26	3.77	1.49	1.14
2	2.39 (2.1)	-0.38	0.13	2.64	0.73	0.80
3	1.88 (1.6)	-0.43	0.10	2.21	0.57	0.67
4	0.29 (0)	-0.66	0.03	0.92	0.09	0.28
	52-59 DAP (ETP=4.14 cm)					
1	6.60 (6.6)	1.56	0.51	4.53	1.59	1.09
2	4.20 (4.2)	0.41	0.01	3.78	1.01	0.91
3	3.60 (3.6)	0.69	0.01	2.90	0.87	0.70
4	0.00 (0)	-0.91	0.01	0.90	0	0.22
	59-70 DAP (ETP=5.99 cm)					
1	8.53 (6.3)	1.13	2.65	4.75	1.42	0.79
2	4.34 (2.1)	-0.18	0.01	4.51	0.72	0.75
3	4.48 (2.24)	0.77	0	3.71	0.75	0.62
4	2.24 (0)	0.63	0	1.61	0.37	0.27

Table 9--continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
			cm			
	70-81 DAP (ETP=5.85 cm)					
1	5.40 (0)	-3.55	4.28	4.67	0.92	0.80
2	5.40 (0)	1.09	0.33	3.98	0.92	0.68
3	5.40 (0)	1.32	0.15	3.93	0.92	0.67
4	5.40 (0)	1.39	0.21	3.80	0.92	0.65
	81-88 DAP (ETP=4.02 cm)					
1	5.93 (2.1)	2.73	0.96	2.24	1.48	0.56
2	5.93 (2.1)	2.44	1.32	2.17	1.48	0.54
3	5.93 (2.1)	2.82	0.47	2.64	1.48	0.66
4	3.84 (0)	1.04	0.12	2.68	0.96	0.67
	88-95 DAP (ETP=3.65 cm)					
1	2.86 (2.1)	-1.88	2.41	2.33	0.78	0.64
2	0.76 (0)	-2.72	1.15	2.33	0.21	0.64
3	0.76 (0)	-2.92	1.06	2.62	0.21	0.72
4	0.76 (0)	-1.52	0.05	2.23	0.21	0.61
	95-102 DAP (ETP=4.00cm)					
1	6.42 (2.1)	1.18	3.02	2.22	1.61	0.56
2	6.42 (2.1)	2.06	1.94	2.42	1.61	0.61
3	4.32 (0)	0.92	0.12	3.28	1.08	0.82
4	4.32 (0)	0.53	0.01	3.78	1.08	0.94
	102-105 DAP (ETP=1.69 cm)					
1	.	.	.	.	.	.
2	0.58 (0)	-0.47	0.16	0.89	0.34	0.53
3	0.58 (0)	-0.55	0.03	1.10	0.34	0.65
4	0.58 (0)	-0.76	0.02	1.32	0.34	0.78
	105-115 DAP (ETP=5.02 cm)					
1	.	.	.	.	.	.
2	.	.	.	.	.	.
3	5.00 (2.1)	0.65	0.22	4.13	1	0.82
4	2.90 (0)	-0.15	0	3.05	0.58	0.61

Table 9 --continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
			cm			
			115-122 DAP (ETP=3.43 cm)			
1	.	.	.	.	.	.
2	.	.	.	.	.	.
3	12.01 (2.1)	3.88	4.77	3.36	3.50	0.98
4	9.91 (0)	4.52	2.57	2.82	2.89	0.82
			122-126 DAP (ETP=2.02 cm)			
1	.	.	.	.	.	.
2	.	.	.	.	.	.
3	0.28 (0)	-3.64	1.94	1.98	0.14	0.98
4	0.28 (0)	-1.81	1.09	1	0.14	0.50
			0-102 DAP (ETP=55.33 cm)			
1	65.42(36.76)	2.00	20.63	41.87	1.18	0.76
2	52.72(24.06)	1.85	11.96	37.32	0.95	0.67
3	48.16(19.5)	1.15	9.39	35.24	0.87	0.64
4	38.61(9.95)	-0.41	8.18	29.74	0.70	0.54

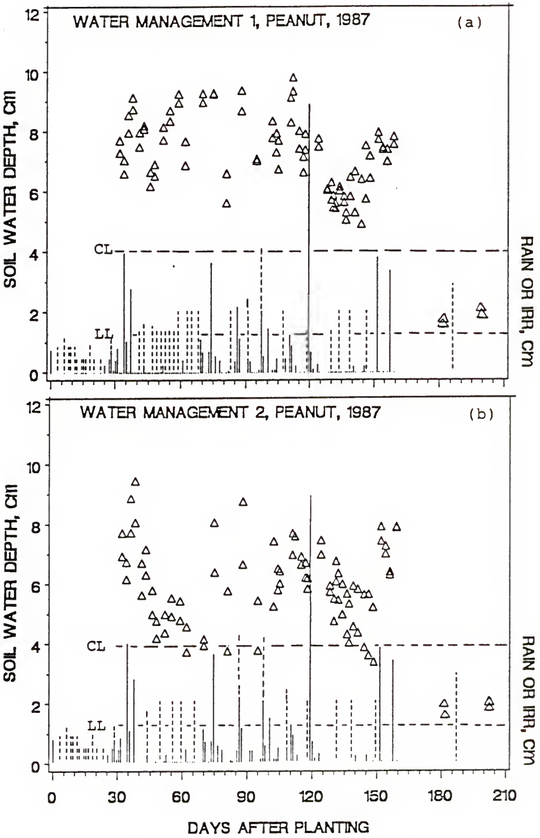


Fig. 20. Daily rainfall, irrigation, and soil water depths in the rhizosphere of sole and intercrop peanut (Southern Runner), IREP, 1987.

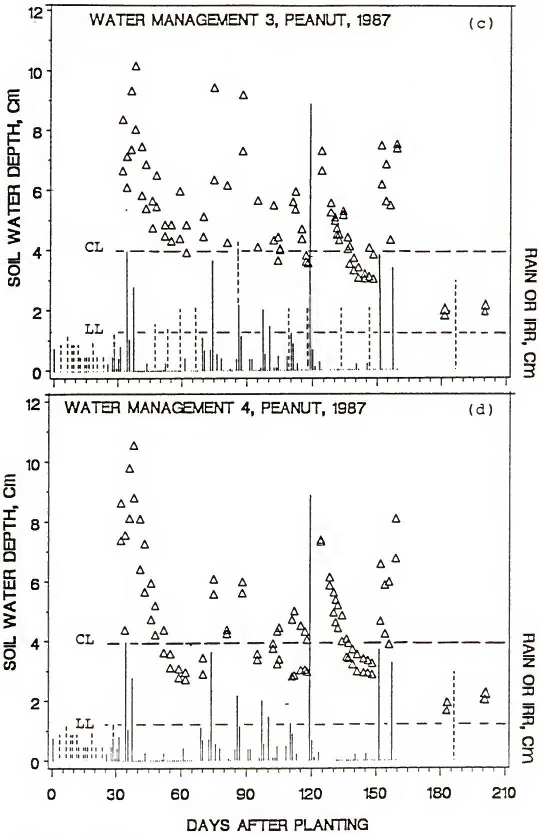


Fig. 20.- Continued

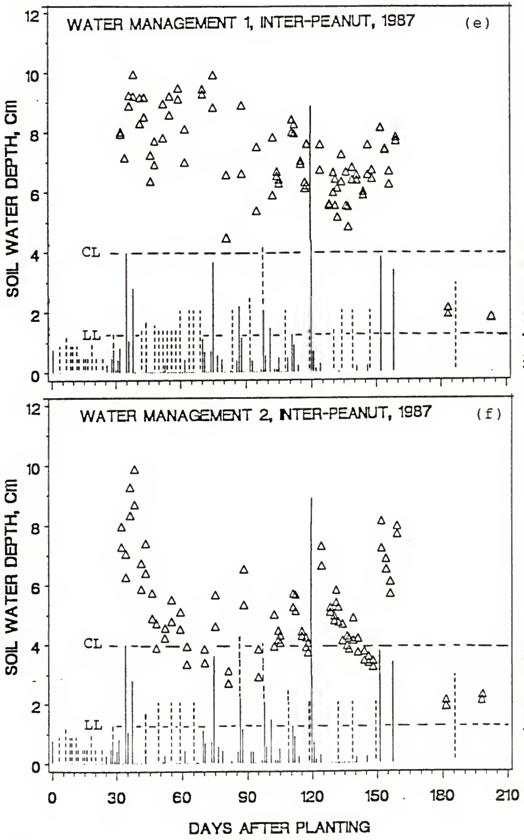


Fig. 20.- Continued

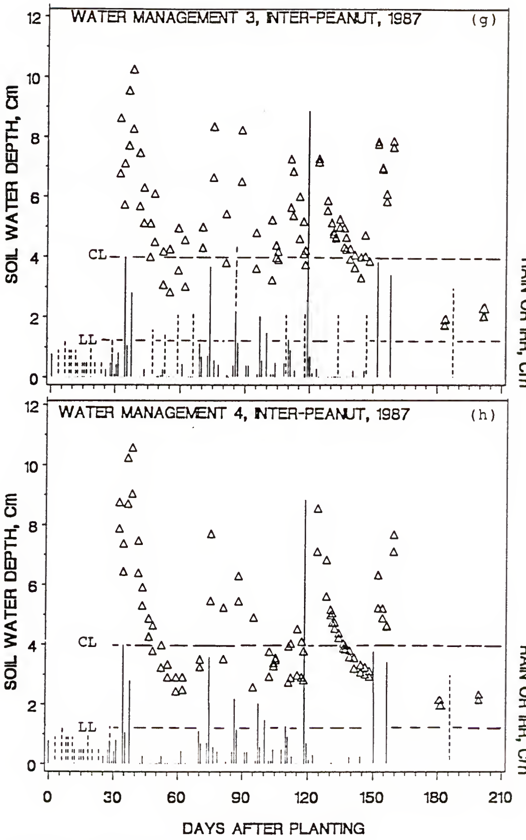


Fig. 20.- Continued

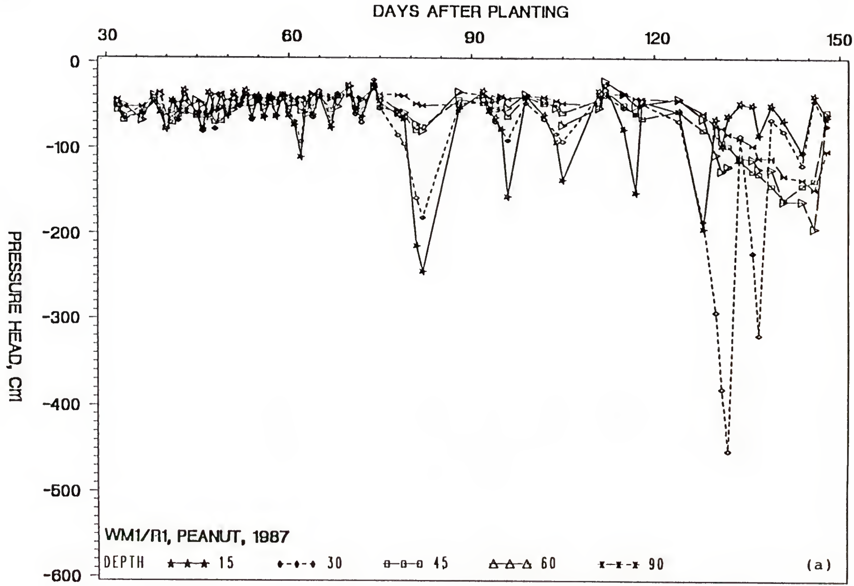


Fig. 21. Daily pressure heads in the root zone of sole peanut (Southern Runner), IREP, 1987.

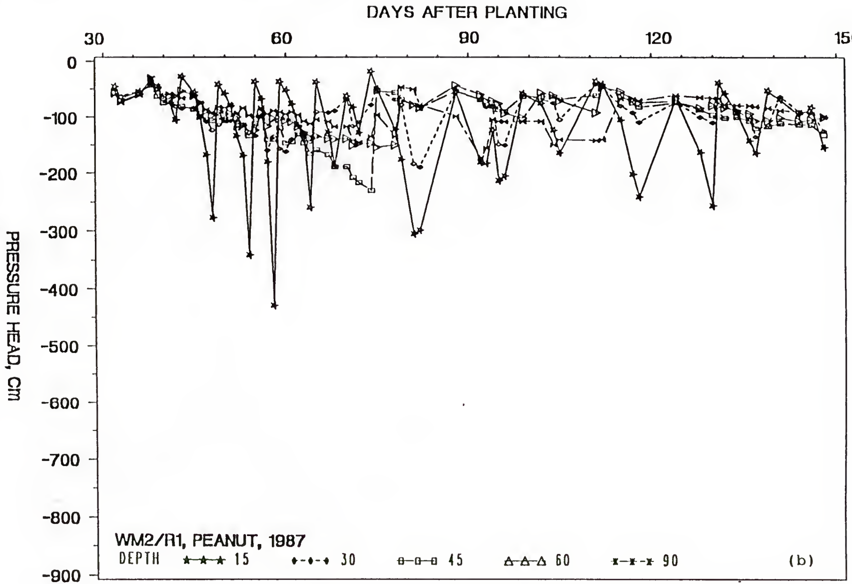


Fig. 21.- continued

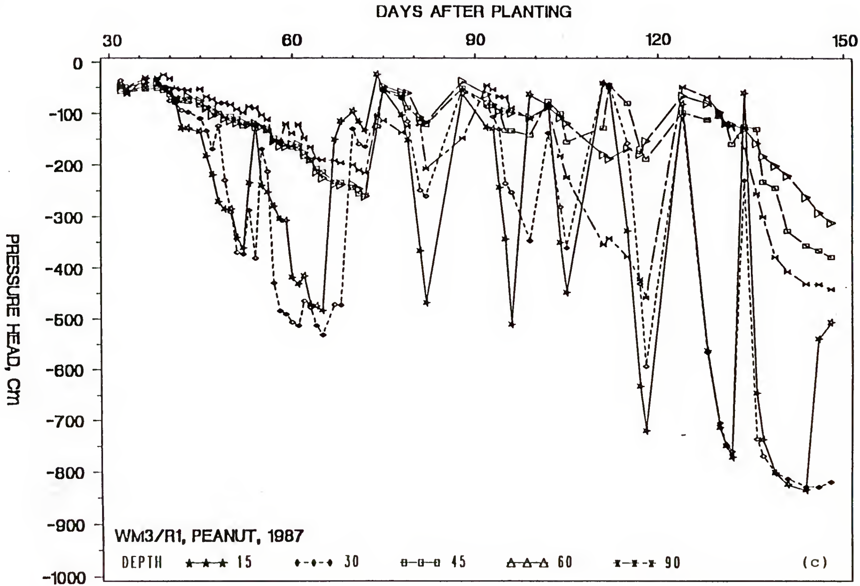


Fig. 21.- Continued

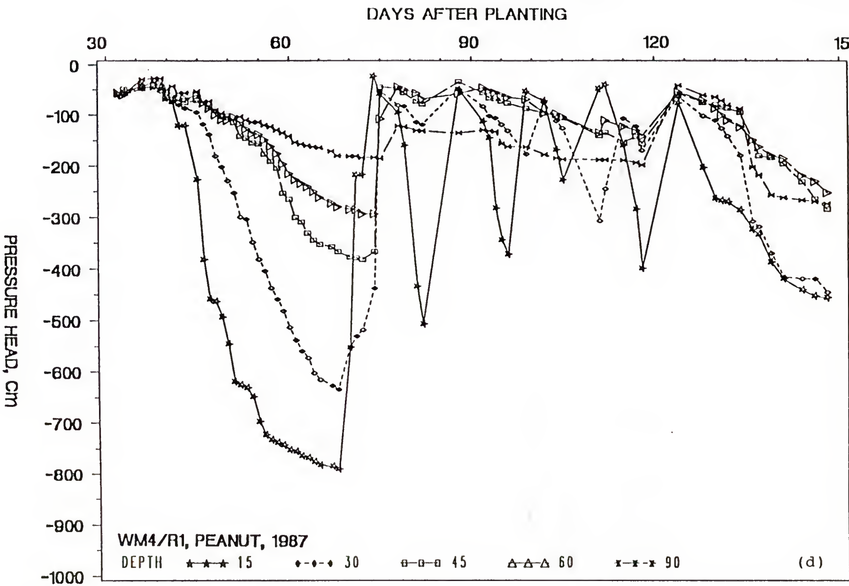


Fig. 21.- Continued

pressure heads and water contents all along the growing season as compared to corn and sorghum subplots. After the harvest of corn crop (122 DAP), irrigation frequency had to be slightly reduced to adapt it to peanut water requirement. After the first peanut harvest at 160 DAP, the crop received only 3 cm of water (at 186 DAP) before the final harvest at 203 days. Peanut crop experienced some water stress at 50-70 DAP (treatments 2, 3 and 4), at 95-122 DAP (treatments 3 and 4), at 130-150 DAP (treatments 2, 3 and 4), and after the first harvest (all treatments). Periodic soil water balance data of Table 10 show a more irregular increase in actual ET rates of peanut than with corn or sorghum (Tables 8 and 9). This is probably due to the indeterminate growth habit of Southern Runner peanut. Peak water consumption rates were attained at 88-102 DAP, but actual ET seldom exceeded potential ET (Penman). All other conditions being equal, intercropping peanut tended to be under more water stress than sole peanut (figures 21a - 21h), but the difference, based on soil water budgets was not significant.

General Discussion and Conclusions

Leaves are certainly the most drought sensitive part of the plant. The coupling of tensiometer readings with observation of crop leaves for visible signs of water stress (rolling or folding of leaves) as used in the 1986 and 1987 experiments for irrigation scheduling revealed that in all treatments, sorghum leaves showed visible signs of water stress earlier than corn and lastly peanut. This may seem contradictory, given the drought tolerance reputation of sorghum species. But in fact, leaf rolling which results in reduced leaf size may be one of the mechanisms of sorghum crop adaptation to droughty conditions. Parker (1968) reported that some grass species in

Table 10: Periodic water balance during the growing season of Southern Runner Peanut, Gainesville, 1987.

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	0-32 DAP (ETP=16.82 cm)					
1	13.54 (9.95)	3.34	4.55	6.05	0.80	0.36
2	13.54 (9.95)	3.06	5.18	5.73	0.80	0.34
3	13.54 (9.95)	3.17	5.10	5.71	0.80	0.34
4	13.54 (9.95)	3.23	5.07	5.72	0.80	0.34
	32-38 DAP (ETP=3.17 cm)					
1	7.98 (0)	1.99	4.47	1.52	2.52	0.48
2	7.98 (0)	1.74	4.64	1.60	2.52	0.50
3	7.98 (0)	1.61	4.72	1.65	2.52	0.52
4	7.98 (0)	1.69	4.57	1.72	2.52	0.54
	38-46 DAP (ETP=4.41 cm)					
1	3.25 (3.0)	-1.98	2.48	2.75	0.74	0.62
2	1.75 (1.5)	-3.36	2.13	2.98	0.40	0.68
3	0.25 (0)	-3.91	2.07	2.09	0.06	0.47
4	0.25 (0)	-4.32	1.83	2.74	0.06	0.62
	46-52 DAP (ETP=3.29 cm)					
1	4.89 (4.6)	1.77	0.90	2.22	1.49	0.67
2	2.39 (2.1)	-0.39	0.40	2.38	0.73	0.72
3	1.88 (1.6)	-0.22	0.36	1.74	0.57	0.53
4	0.29 (0)	-1.09	0.25	1.13	0.09	0.34
	52-59 DAP (ETP=4.14 cm)					
1	6.60 (6.6)	0.92	2.63	3.05	1.59	0.74
2	4.20 (4.2)	0.36	0.14	3.70	1.01	0.89
3	3.60 (3.6)	0.51	0.28	2.81	0.87	0.68
4	0.00 (0)	-0.74	-0.77	1.51	0	0.36
	59-70 DAP (ETP=5.99 cm)					
1	8.53 (6.3)	0.69	3.91	3.93	1.42	0.66
2	4.34 (2.1)	-0.71	0.03	5.02	0.72	0.84
3	4.48 (2.24)	0.37	-0.09	4.20	0.75	0.70
4	2.24 (0)	0.59	-0.10	1.75	0.37	0.29

Table 10--continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	70-81 DAP (ETP=5.85 cm)					
1	5.40 (0)	-3.69	4.63	4.46	0.92	0.76
2	5.40 (0)	0.37	0.08	4.95	0.92	0.85
3	5.40 (0)	0.30	0.29	4.81	0.92	0.82
4	5.40 (0)	0.80	0.06	4.54	0.92	0.78
	81-88 DAP (ETP=4.02 cm)					
1	5.93 (2.1)	2.91	0.53	2.49	1.48	0.62
2	5.93 (2.1)	2.93	0.40	2.60	1.48	0.65
3	5.93 (2.1)	3.04	0.44	2.45	1.48	0.61
4	3.84 (0)	1.49	0.05	2.30	0.96	0.57
	88-95 DAP (ETP=3.65 cm)					
1	2.86 (2.1)	-1.98	1.71	3.13	0.78	0.86
2	0.76 (0)	-3.08	0.16	3.68	0.21	1.01
3	0.76 (0)	-3.17	0.54	3.39	0.21	0.93
4	0.76 (0)	-2.32	0.01	3.07	0.21	0.84
	95-102 DAP (ETP=4.00cm)					
1	6.42 (2.1)	1.13	2.27	3.02	1.61	0.76
2	6.42 (2.1)	1.42	1.26	3.64	1.61	0.91
3	4.32 (0)	0.93	0.06	3.33	1.08	0.83
4	4.32 (0)	0.47	0	3.85	1.08	0.96
	102-105 DAP (ETP=1.69 cm)					
1	0.58 (0)	-0.91	0.53	0.96	0.34	0.57
2	0.58 (0)	-0.86	0.15	1.29	0.34	0.76
3	0.58 (0)	-0.80	0.03	1.35	0.34	0.80
4	0.58 (0)	-0.17	0	0.75	0.34	0.44
	105-115 DAP (ETP=5.02 cm)					
1	5.00 (2.1)	0.62	0.56	3.82	1	0.76
2	5.00 (2.1)	0.52	0.80	3.68	1	0.73
3	5.00 (2.1)	0.49	0.61	3.90	1	0.78
4	2.90 (0)	-0.45	0	3.35	0.58	0.67

Table 10--continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	115-122 DAP (ETP=3.43 cm)					
1	11.40 (1.5)	3.14	5.93	2.67	3.32	0.78
2	12.01 (2.1)	3.41	5.56	2.52	3.50	0.89
3	12.01 (2.1)	3.67	5.26	2.52	3.50	0.73
4	9.91 (0)	4.94	2.61	2.36	2.89	0.69
	122-130 DAP (ETP=4.05 cm)					
1	1.78 (1.6)	-4.84	3.13	3.49	0.44	0.86
2	0.28 (0)	-2.99	0.78	3.49	0.07	0.86
3	0.28 (0)	-3.35	1.30	2.88	0.07	0.71
4	0.28 (0)	-2.46	0.88	1.86	0.07	0.46
	130-139 DAP (ETP=4.91 cm)					
1	4.20 (4.2)	0.32	0.42	3.76	0.86	0.76
2	4.20 (4.2)	0.73	0.47	3.11	0.86	0.63
3	2.10 (2.1)	-1.00	0.04	3.06	0.43	0.62
4	0.00 (0)	-1.64	-0.09	1.73	0	0.35
	139-146 DAP (ETP=2.62 cm)					
1	2.52 (2.1)	-0.02	0.15	2.09	0.96	0.80
2	0.42 (0)	-1.12	0.09	1.95	0.16	0.74
3	2.52 (2.1)	0.07	-0.01	2.11	0.96	0.80
4	0.42 (0)	-0.29	-0.03	0.74	0.16	0.28
	146-156 DAP (ETP=4.53 cm)					
1	3.90 (0)	-0.01	1.38	3.12	0.86	0.69
2	6.00 (2.1)	2.21	1.08	2.71	1.32	0.60
3	3.90 (0)	1.62	0.01	2.27	0.86	0.50
4	3.90 (0)	1.79	0	2.11	0.86	0.47
	156-160 DAP (ETP=1.72 cm)					
1	3.45 (0)	0.67	1.73	1.05	2	0.61
2	3.45 (0)	0.72	1.74	0.99	2	0.58
3	3.45 (0)	2.02	0.51	0.93	2	0.54
4	3.45 (0)	2.15	0.23	1.07	2	0.62

Table 10 -- continued

WM	INPUT (IRR)	ΔS	DRAIN-AGE	ETA	INPUT/ETP	ETA/ETP
	cm					
	160-186 DAP (ETP=8.26 cm)					
1	0	-5.50	0.30	5.20	0	0.63
2	0	-6.12	0.42	5.40	0	0.65
3	0	-6.03	0.22	4.89	0	0.59
4	0	-5.98	0.13	4.68	0	0.57
	186-203 DAP (ETP=4.45 cm)					
1	3.00 (3.0)	0.09	0	2.91	0.67	0.65
2	3.00 (3.0)	0.05	0	2.95	0.67	0.66
3	3.00 (3.0)	0.11	0	2.89	0.67	0.65
4	3.00 (3.0)	0.15	0	2.85	0.67	0.64
	0-203 DAP (ETP=96.03 cm)					
1	101.25(51.1)	-1.67	42.22	61.71	1.05	0.64
2	87.65(37.55)	-0.86	25.96	63.22	0.91	0.66
3	80.99(30.89)	-0.87	22.04	60.38	0.84	0.63
4	63.05(12.95)	-2.16	14.93	49.84	0.66	0.52

the Mediterranean region can reduce transpiration as much as 46 to 63% by rolling their leaves. But he did not provide any indication on the associated effect of such reductions on photosynthesis. Sorghum is known to become somewhat dormant under extreme drought conditions, but without withering or dying (House, 1978). This was observed during the 1987 season in treatments 3 and 4. Since leaf rolling may not occur in some species until plant water deficit reaches lethal levels, the use of leaf visible signs of water stress alone may not be a reliable index of plant water status. Corn crop seems to experience more damaging plant water deficit before showing any external sign of water stress.

Figure 22 depicts the comparison among average daily ET rates for corn (C), sorghum (S) and peanut (P) in water managements 1, 2, 3 and 4, as well as average daily potential ET calculated by Penman method (X), Turc method (Y), or measured with a class A pan (Z) for arbitrarily selected time intervals during the 1987 growing season. The analysis of covariance of average ET rates showed a significant effect of both crop and water management, and an interaction between these two factors ($p = 0.05$). But no significant difference was found between the two cropping systems, even though intercrop peanut and sorghum exhibited slightly higher ET rates than the corresponding sole crops. Evapotranspiration values on figure 22 represent averages over the two cropping systems for sorghum and peanut, respectively.

The three crops differed in their water-use patterns during the growing season, and for a given crop, ET rates varied with growth stage. Peanut crop exhibited lower ET rates than the two grasses from planting until 70-81 DAP and 102-105 DAP, respectively, when sorghum and then corn ET were declining, probably because of leaf senescence. The same pattern was observed during the 1986 experiment where only

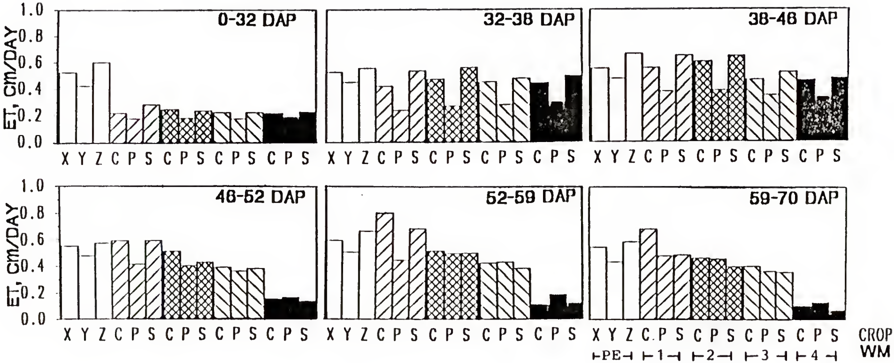


Fig. 22. Average daily evapotranspiration calculated at arbitrary time intervals for corn (C), sorghum (S), and peanut (P) in water managements 1, 2, 3, and 4, and potential ET (PE) calculated by Penman (X), Turc (Y) or pan class A (Z) methods, IREP, 1987.

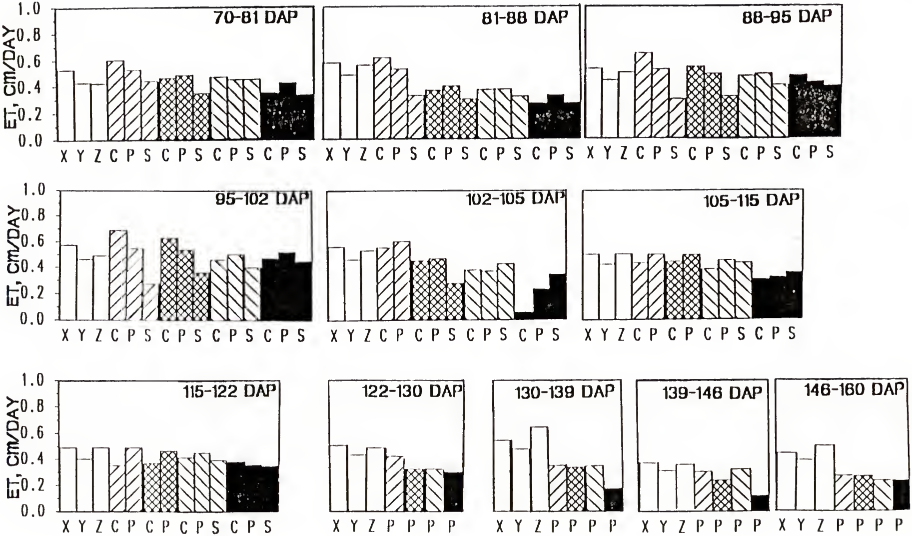


Fig. 22.- Continued

peanut (Florunner) and sorghum were present. Southern Runner peanut is known for its slow development early in the season and a more indeterminate growth habit as compared to Florunner (Gorbet et al., 1986). This may explain the difference in peanut water uptake patterns between the two growing season. The 1987 ET pattern did not show a marked peak water consumption in peanut, and the actual ET seldom reached or exceeded potential rates based on Penman's formula. Peak consumptions were observed in all other crops (1986 peanut, 1986 and 1987 sorghum, and 1987 corn) where ETA/ETP ratios (crop coefficients) exceeded one. Several authors have reported crop coefficients greater than one at mid-season for corn, peanut and sorghum (Doorenbos and Pruitt, 1977; Jones et al., 1984; Stansell et al., 1976; Doss et al., 1965), due probably to a combined effect of canopy structure and roughness, physiological processes and advective transfers of energy (oasis or clothesline effects). In times of high wind speed and low relative humidity of the air, advection effect may have been greater in corn than in sorghum and lastly peanut because of their different respective heights and the proximity in which they were planted. There seems to be no ideal plot size which would achieve an advection-free water uptake from an irrigated cropped land (Viets, 1962). The quantitative significance of advection over the growing season was certainly limited as illustrated by the average seasonal crop coefficients.

In conclusion, the observed differential water uptake patterns of corn, sorghum and peanut may be attributable to their respective differential growth habits, and also to their canopy structure and roughness. The next chapter will analyze how such information can be integrated into cropping systems in order to optimize crop yield and water-use efficiency.

CHAPTER 4
CROP YIELD AND WATER USE

Introduction and Literature Review

Considering the scarcity and/or poor quality of water in many parts of the world, problems regarding irrigation scheduling and crop water-use efficiency have become increasingly important. It is now realized that on-farm water management strategies should be aimed at optimizing water use and economic return, rather than maximizing yield per unit area.

Crop Yield and Water-Use Efficiency

Viets (1962) defined water-use efficiency as the ratio of the yield obtained to the amount of water used. However, the yield can be defined in terms of total dry matter, above ground dry matter, or marketable product. Moreover, the amount of water used can be taken to include transpiration, evapotranspiration, or irrigation. From an engineering point of view, parameters such as conveyance efficiency, application efficiency, uniformity coefficient, deficit efficiency distribution, and requirement distribution efficiency . . . are commonly used to evaluate the performance of an irrigation system, and will not be examined in this literature review. Water-use efficiency can also be defined at the leaf photosynthetic level as the ratio of photosynthetic carbon dioxide exchange rate (CER) to transpiration rate (TR).

Transpirational WUE is necessarily connected to stomatal control of gas exchange rates at the leaf-atmosphere boundary. The light-induced opening of stomates during the day to take in $C0_2$ necessary for photosynthesis also allows water vapor to escape, in response to the evaporative demand of the atmosphere. The theoretical basis for WUE can be derived from the respective gradients of $C0_2$ and water vapor. Photosynthesis and transpiration can be represented as gas gradients divided by resistances as follows (Bierhuizen and Slatyer, 1965; Boyer, 1985):

$$CER = \frac{Ca - Cc^{*}}{Rs+Ra+Rm} = \frac{\Delta C0_2}{Rs+Ra+Rm} \qquad [35]$$

$$TR = \frac{Wi - Wa}{R's + R'a} = \frac{\varepsilon\, \rho_a}{Pa}\ \frac{\Delta e}{R's + R'a} \qquad [36]$$

where CER is the carbon exchange rate (mol m^{-2} s^{-1}) TR, rate of transpiration (mol m^{-2} s^{-1})

Ca and Cc are the corresponding mole fractions of $C0_2$ in the bulk air and at the $C0_2$ fixation site (chloroplast);

$\Delta C0_2$ is the $C0_2$ gradient between the air and the chloroplast;

Wi and Wa are the corresponding mole fractions of water vapor inside the leaf and in the bulk air;

Rs and Ra, R's and R'a are stomatal and boundary layer resistances to $C0_2$ and water vapor diffusion, respectively;

Rm is the mesophyll resistance to $C0_2$ diffusion in the liquid phase;

Δe is the vapor pressure deficit between leaf and air;

ε is the ratio of the mole weight of water vapor to air;

ρ_a is air density and Pa is atmospheric pressure.

Photosynthetic water-use efficiency can then be expressed as

$$WUE = \frac{Pa}{\varepsilon\rho_a} \frac{1}{\Delta e} \left(\frac{R's + R'a}{Rs+Ra+Rm}\right) \Delta CO_2 \qquad [37]$$

Eq. [37] indicates that photosynthetic water-use efficiency is directly proportional to the CO_2 gradient and indirectly proportional to the vapor pressure deficit gradient between the bulk air and the CO_2 fixation site. This implies that: (1) a given crop grown in different climatic zones represented by various vapor pressure deficits Δe may exhibit different WUE; (2) all other conditions being equal, C_4 plants would be expected to have a greater WUE than C_3 because of the biochemical and enzymatic differences in their respective photosynthetic pathways.

El-Sharkawy et al. (1967), among others, suggested that comparisons of photosynthetic or transpirational rates among varieties or species be made at similar stomatal resistance. In such conditions, these authors reported that the rate of transpiration of C_4 species (Sorghum vulgare, Zea mays) was similar to that of C_3 species (Gossypium hirsutum, Beta vulgaris, Helianthus annus). However, CO_2 fixation rate was about two-thirds higher in C_4 at equal stomatal openings because of a greater CO_2 gradient, resulting in a similar advantage in WUE. The C_4 WUE advantage over C_3 increases with air temperature up to 30-35°C (Boyer, 1970) but the C_4 pathway itself may not confer any special tolerance to water stress (Bierhuizen, 1976; Hsiao et al., 1976; Levitt, 1976) as evidenced by the lack of tolerance of corn to drought compared to soybean (Boyer, 1970). Even though corn had a higher CO_2 assimilation rate during

favorable water conditions, inhibition of photosynthesis due to stomatal closure began at higher leaf water potentials (-3.5 bars) in corn than in soybean (-11 bars).

The higher mesophyll resistance (Rm) of C_3 can also have an influence on the differential WUE between C_4 and C_3 species. With a high value of Rm, stomatal closure tends to reduce transpiration more than it does for net photosynthesis, thus increasing the water-use efficiency (Stanhill, 1972). By contrast, in species with a low value of Rm (corn, sorghum), it can be expected that the percentage decline in water use and net photosynthesis would be about the same. Van Hoorn et al. (1969) submitted sorghum and alfalfa to various irrigation strategies and water stress conditions; they reported that the evapotranspirational WUE was independent of the irrigation treatment in sorghum, but in alfalfa a lower water supply increased water-use efficiency as much as 49%. On the other hand, Hillel and Guron (1973) reported a reverse situation when they found in a 5-year experiment that ET water-use efficiency of corn systematically increased with increased irrigation which maintained continuous high soil water conditions in the root zone. The apparent contradiction between these two sets of results may be due to the differential response of the respective crops to soil water status.

The greater CO_2 uptake rate of C_4 plants as compared to C_3 at a given transpiration rate observed at the leaf level carries over into actual field data (Downes, 1969). The twofold WUE superiority of C_4 occurs over a wide range of environmental and physiological conditions, and is due almost entirely to a higher photosynthetic rate rather than a lower transpiration rate (Ludlow and Wilson, 1972). But it would be inaccurate and too simplistic to classify crops and their water relations on the basis of the photosynthetic pathway alone, since enormous differences and overlaps exist among

species, even varieties within the same species as were reported by Sullivan and Blum (1970) and Hsiao et al. (1976) between sorghum and corn.

As a consequence of the functional relationship between $C0_2$ uptake and water vapor escape at the leaf level, dry matter yield which is the final output of photosynthesis would be expected to be highly correlated to transpiration. Linear relationships between final dry matter yield and seasonal transpiration have been described for most agronomic crops (de Wit, 1958; Viets, 1962; Arkley, 1963; Tanner and Sinclair, 1983). De Wit (1958) showed that for dry, high-radiation climates, total dry matter yield Y ($kg.ha^{-1}$) and seasonal transpiration T (cm) were related as

$$Y/T = m/Tmax \qquad [38]$$

where Tmax (cm day^{-1}) is mean daily free water evaporation during the growing season and m (kg ha^{-1} day^{-1}) is a constant dependent on crop species. DeWit proposed a simplified form of Eq. [38] for humid climates,

$$Y/T = n \qquad [39]$$

where n is a constant.

From the review of early literature, Tanner and Sinclair (1983), and Hanks (1983) found that the relative ranking of corn, sorghum, and millets giving the highest values of m, followed by other grain cereals, potato, and lastly legumes remained consistent throughout time and locations. But the high variability of m among locations for a given species suggests either an inadequacy in de Wit's approach or the interaction of factors other than water. Kanemasu (1983) suggested that the observed

variation in the value of m is probably due to the problems associated with an appropriate means of normalizing T.

Hanks (1974) derived a model from Eq. [38] by introducing the maximum yield corresponding to maximum transpiration as a way of correcting for the differential sensitivities of biomass and marketable yields to water deficits at different growth stages,

$$Y/Ymax = T/Tmax. \qquad [40]$$

Eq. [40] assumes that the linear relation applies to only one growing season and is most useful for comparing conditions or treatments within a given year. But transpiration is difficult to measure under field conditions where crop water use is usually expressed in terms of actual evapotranspiration or irrigation. Field-determined linear crop water production functions using total dry matter yield and either seasonal ET or irrigation have been reported (Arkley, 1963; Hanks et al., 1969; Stewart et al., 1977; Riestra-Diaz, 1984). But yield response to water management is an extremely dynamic and complex process because of the multiplicity of interactions among the yield-determining plant parameters under limited water conditions. This is particularly true when relating marketable yield to water use (Kanemasu, 1983). Both linear (Stewart et al., 1977; Hammond et al., 1981a and 1981b; Jones et al., 1984; Hammond and Bennett, 1988) and curvilinear (Stewart and Hagan, 1973; Hillel and Guron, 1973; Musick et al., 1976) relationships between grain yield and seasonal ET or irrigation amount have been reported. Timing, severity and duration of soil water deficits during the crop ontogeny, and the complex interplay between water stress and other environmental variables are certainly important to the shape of the resulting marketable

yield-water use functions. It is therefore evident that different yields can be obtained for the same amount of seasonal irrigation or ET. Soil water deficits occurring at more sensitive crop growth stages would be expected to have a more deleterious effect on marketable yield as compared with deficits at other stages. Stewart et al. (1976) suggested that linear relationships are obtained when scheduling of water deficits is optimized in such a way that any seasonal ET deficit results in a minimum grain yield loss. This implies that water deficits do not significantly alter the crop harvest index (defined as the ratio of grain to total dry matter yield) (Sinclair et al., 1984). Such considerations are highly crop-specific. Curvilinear production functions may result from over-irrigation (i.e. irrigation in excess of the amount required for maximum yield) and/or over-estimation of actual ET by not accounting for the amount of water lost by deep drainage beyond the rhizosphere (Barrett and Skogerboe, 1980). Stegman et al. (1980) pointed out that the non-ET losses of water applied were due to inefficiencies in the irrigation methods and strategies.

Stewart et al. (1977) devised a model to predict dry matter yield from actual ET as follows:

$$Y/Ymax = 1-\beta_0\ ET_D = 1-\beta_0+\beta_0\ ET/ETmax \qquad [41]$$

where β_0 is the slope of relative yield vs. ET deficit (ET deficit = ET_D = 1-ET/ETmax). When Y/Ymax = 0, soil evaporation can be approximated by the ratio ET/ETmax. The portion of ETmax that is Tmax is equal to $1/\beta_0$. Thus a β_0 of 1.0 would mean no water loss by direct evaporation from the soil. The value of β_0 must be equal or greater than 1.0 (Hanks, 1983).

Comparing Eq. [38] and [41] reveals that de Wit's factor m can be computed as

$$m = Ymax\ Tmax\ \beta_0/ETmax \qquad [42]$$

where Tmax is the average maximum daily transpiration, cm/day, ETmax is the maximum seasonal ET, cm, and Ymax is the maximum dry matter yield, kg/ha.

Dry matter-ET relationships are attractive because of their inherent simplicity. However, in estimating grain yields, the Y-ET relationships are not unique because of complex interactions among crop development, assimilate partitioning and environment. It is doubtful that such relationships can be successfully extended to climatically diverse regions. Moreover, Hillel and Guron (1973) pointed out that yield is not strictly proportional to ET because even if production appears to increase linearly with ET, there is a distinct intercept or threshold value of ET below which production is negligible. If all the water received on the crop area is used for crop transpiration, slopes of the T and ET functions should be the same. However, the slope of the T function is generally greater than that of the ET function. As pointed out by Viets (1962), the Y/ET will continue to increase asymptotically with improved management until it reaches the Y/T line which is the upper limit. Moreover, if all of the irrigation water is used for evapotranspiration, slopes of the ET and irrigation functions should be similar. But, the irrigation function always has a smaller slope than the ET function. Stewart and Hagan (1973), Stegman et al. (1980), and Hammond et al. (1981a) have used the ratio of the two slopes as a measure of irrigation-use efficiency for the specific experiment.

Optimization of Field Water-Use Efficiency

Viets (1962), Stewart et al. (1973), Tanner and Sinclair (1983) recognized the economic aspects of irrigation management. The farmer is more concerned with

minimizing the cost of the water used while improving its economic return by maximizing crop water-use efficiency, than with biomass productivity as such. Viets (1962) pointed out that attaining maximum ET efficiency was not always desirable. Where water is limited, Stewart et al. (1973) recommended to combine irrigation efficiency with the economic component of farming system by reducing seasonal irrigation water from the yield-maximizing levels to the level at which marginal input cost equals the value of the marginal yield (economic break-even point). Conversely, Hillel (1972) suggested that the basic goal in water management is not to save water but to increase production efficiency by optimizing the water supply in conjunction with other environmental variables in order to maximize crop response. The best water management strategy should therefore be designed to obviate water stress and prevent water from becoming a limiting factor. Stegman et al. (1980) stated that water management practices should be designed to: (a) maximize yield per unit of land area, (b) maximize yield per unit of water applied, (c) maximize net profit, and (d) minimize energy cost. Viets (1962) pointed out that WUE is a constant only when plants are grown in widely spaced containers having sealed surfaces to prevent any evaporation. He further concluded that there was considerable opportunity to increase the ratio of yield to water use in the field. Hillel and Guron (1973) suggested that the said ratio could be increased by either increasing the numerator or decreasing the denominator. But in actual practice it would be more promising to attempt to improve water-use efficiency by increasing plant production than by decreasing evapotranspiration, since plants growing in the field are subject to an externally imposed evaporative demand. Fischer and Turner (1978) concluded that when increased water-use efficiency is found as a result of improved management, the increases result from increased transpiration

as a fraction of the ET; evapotranspiration efficiency is increased although transpiration efficiency is changed little, if any.

Improving WUE by irrigation strategy

Many investigators tended to accept the hypothesis of virtually equal availability of soil water to crops within the range between the so-called field capacity and permanent wilting percentage. But increasing evidence has been accumulating (Viets, 1966; Hillel and Guron, 1973; Bierhuizen, 1976) that crops may show a pronounced increase in yield when soil water is obviated as a limiting factor, that is, when the root zone soil matric potential is kept continuously high, provided that the soil is not so wet as to restrict aeration, nor is the irrigation amount so excessive as to waste water and leach nutrients. In sandy soils, such conditions can be met by light but frequent irrigation applications, with the amount of water adjusted to crop growth stages. Threshold values of soil water potential at which marketable yield declines depend on weather, soil, and plant conditions (Bierhuizen, 1976). Generally, periods of maximum sensitivity to drought occur during the shift from the vegetative to the reproductive phase. These sensitive periods should be integrated in the irrigation strategy. Water applications should be sequenced in such a way that soil water deficits occur at the least damaging times so that they cause the least possible reduction in crop yield (Barrett and Skogerboe, 1980).

Hiler and Clark (1971), and Hiler et al. (1974) introduced the Stress Day Index (SDI) concept as a quantitative means for determining the stress imposed on a crop during its growth cycle:

$$SDI = \sum_{i=1}^{n} (SD_i \times CS_i) \ldots \qquad [43]$$

where n represents the number of growth periods considered, SD the stress day factor which is a measure of the degree and duration of the plant water deficit, and CS the crop susceptibility factor which depends on the species and stage of development. These authors proposed several alternatives for determining the input parameters of the model.

Jensen (1968) derived a multiplicative type model relating the effects of soil water deficit on grain yield:

$$Ya/Ym = \prod_{i=1}^{n} (ETa/ETp)_i^{\lambda i} \qquad [44]$$

where Ya/Ym is the relative marketable yield, ETa/ETp is the relative evapotranspiration during growth stage i, λi is the relative sensitivity of the crop to water deficit in growth stage i, and n is the number of growth stages considered. This model implies that some nonlinearity between yield and seasonal ET may occur at various growth stages. Using Jensen's model, Tsakiris (1982) proposed a method for the determination of the crop sensitivity indices which can be used in optimizing the intraseasonal water distribution when the available irrigation water for the season is limited.

Jackson et al. (1977) developed a stress degree day (SDD) for scheduling irrigation, based on the difference between the canopy temperature and the surrounding air temperature. Rhoads (1981) proposed a management strategy integrating water and fertilizer management for Florida Ultisols. The system is based on the regular application of enough irrigation water to recharge the soil profile to plow depth before it is depleted beyond critical levels, and the periodic addition of fertilizers to meet mineral nutrition needs of the crops. Rhoads achieved highest corn yields by

maintaining the soil-water matric potential in the plow layer at - 200 mbar or above throughout the growing season.

As a summary, methods of application, timing, application intensity and amounts greatly affect the partitioning of input water among the soil water budget components. The objective of the SDI irrigation strategy is to maximize yields per unit of water applied, especially in areas where water is a limiting resource. But the method requires the determination of SDi and CSi for a particular crop-soil-climate system during preliminary experiments where a total control on water application is possible.

Jensen's model follows the same objective as the SDI. The stress degree day method requires the measurement of canopy temperatures and needs to be calibrated for any specific crops. Rhoads' management strategy is designed to maximize crop yield under the assumption of unlimited water resources. But because of the erratic rainfall distribution in Florida during the growing season, there is a high potential for water and fertilizer leaching when unexpected heavy rainfall events occur after the plow layer has been completely replenished by irrigation. Moreover, the threshold matric potential in the plow layer should be adjusted to the type of soil, crop and growth stage. Also, some water deficits at certain growth stages may be necessary to increase some marketable yield qualities.

Improving field WUE by cropping systems

Intercropping has been practiced for generations in many parts of the world as a means of increasing productivity. Trenbath (1974) and Loomis (1983) suggested that intercropping would be less water-use efficient and would seldom outyield the best sole cropping. Overlapping intercrops may require reduction in ground cover for the second crop to be successfully established within the first. The fraction of water lost to

evaporation would thereby be increased. A common assumption about crop mixtures is that different species would complement each other through their differential use of natural resources (Willey, 1979). Thus, competition would be more severe between like things than between unlike things. But de Wit (1960) stated that such assumptions are not true in annual crops which generally compete for the same basic resources of light, CO_2, soil water and nutrients. Loomis (1983) suggested that the photosynthetic rate of a full canopy of leaves of high physiological capacity and arranged in an optimal way can be maximized with a single species, and it cannot be improved by introducing a species with inferior traits. Similarly, complementation of species with deep and shallow rooting cannot exceed in nutrient and water extraction a single species capable of exploring the entire profile. Furthermore, mixed cropping is generally practiced in primitive systems where soil nutrients are strongly limiting. In such conditions, plant growth is generally poor and there is little competition for light. Loomis' analysis implicitly implies that the often reported yield advantages of intercropping over sole cropping may result from a poor management of sole cropping rather than a better or more efficient use of available resources by intercrop systems as suggested by Natarajan and Willey (1980), Reddy and Willey (1981), Marshall and Willey (1983). Harris et al. (1987) stated that yield advantages from intercrops can arise in two ways. Component crops may have different durations of growth cycles or different growth patterns, and thus have peak demands on resources at different times. In both cases, this would lead to better temporal use of resources as found by Willey (1979), Natarajan and Willey (1980). Harris et al. (1987) further stated that there was not enough evidence that intercropping can result in a better spatial use of water, nutrients

or light, although Reddy and Willey (1981) have shown increased efficiency in the spatial use of light in a millet and peanut combination.

Natarajan and Willey (1980) suggested that greater yield stability between seasons in probably the main reason for the prevalence of intercropping in low input agriculture of semi-arid areas rather than higher yields per se. In India, Natarajan and Willey (1986), Harris et al. (1987) and Harris and Nataragan (1987) showed that intercrops of grain sorghum and peanut achieved larger relative yield advantages when grown under drought than they did when kept well-watered. They suggested that the sorghum-peanut mixture may combine both temporal and spatial complementarities, which results in larger yield benefits.

Willey (1985) pointed out that one of the most problematic areas of intercropping research is the quantitative evaluation of the advantages provided by any given intercropping system. Conventionally, the biological efficiency of intercropping is determined by comparing the productivity of a given area of intercropping with productivity if the same area were to be divided between sole crops to give the same ratio of the two crops as in intercropping. Willey (1985) recommended that this ratio be expressed in terms of actual production rather than initial sown proportions. The conventional approach has been to use relative yields which can be added (even though the component crops may be of different kinds) to form a relative yield total on a per plant basis (de Wit and van der Bergh, 1965) or the land equivalent ratio (LER) (Willey, 1979) on a land area basis. The latter is defined as the relative land area required as sole crops to produce the yields achieved in intercropping. For two crops A and B, total LER can be expressed as

$$TLER = \frac{Y_{iA}}{Y_{AA}} + \frac{Y_{iB}}{Y_{BB}} \qquad [45]$$

where Y_{iA} and Y_{AA}, Y_{iB} and Y_{BB} are the respective yields of intercropping and sole cropping for the two crops in the mixture. A total LER greater than one would indicate a yield advantage of intercrop over sole crop. But the LER concept is commonly criticized because it gives no indication of absolute yields. Willey (1985) suggested that absolute yields be used to compare intercropping and sole cropping. He introduced the concept of equivalent yields of sole crops:

$$EY_{AA} = Y_{AA} \quad \{(\frac{Y_{iA}}{Y_{AA}}) \,/\, TLER\} \qquad [46]$$

and $$EY_{BB} = Y_{BB} \quad \{(\frac{Y_{iB}}{Y_{BB}}) \,/\, TLER\} \qquad [47]$$

where EY_{AA} and EY_{BB} are the equivalent absolute yields of sole crops A and B, respectively. The equivalent yield corresponds in absolute terms to TLER = 1 which represents a unit area of sole crops divided to give the same yield ratio as in intercropping.

Hiebsch and McCollum (1987) proposed an area-time equivalency ratio (ATER) developed by integrating the time factor into the land equivalent ratio concept to account for the differential duration of growing seasons in pure stand and intercrop:

$$ATER = \frac{Y_{iA} \cdot T_{AA}}{Y_{AA} \cdot T_{AB}} + \frac{Y_{iB} \cdot T_{BB}}{Y_{BB} \cdot T_{AB}} \qquad [48]$$

where T_{AA} and T_{BB} are the durations of crop cycle in pure stands of crop A and B, respectively; T_{AB} is the total duration required to grow the component crops A and B in the mixture.

After reviewing earlier experiments, Hiebsch and McCollum (1987) did not find any significant yield advantage of intercropping over sole cropping, based on the ATER concept.

Another area of interest in comparing cropping systems is the density of planting. Willey (1979) pointed out that where intercropping gives a yield advantage, the total optimum population may be higher than that of either sole crop. In order to assess any advantage, it is therefore critical that both cropping systems be grown under their respective optimal density combinations. Such density optimizations usually require factorial experiments where planting geometry, density and crop proportions are used as factors.

To summarize this literature review, it appears that very few opportunities are currently available for increasing transpirational water-use efficiency of a crop grown in a given environment. Improving ET and irrigation efficiencies through better management of water and crops seems to be more promising. In practice, increasing WUE by increasing yield presents more possibilities than by decreasing water use. But as pointed out by Tanner and Sinclair (1983), there are limits to the improvements such management strategies can provide. The irrigation water-use efficiency can only approach ET efficiency which in turn approaches the T efficiency as the upper limit.

Materials and Methods

The data collected during the 1986 and 1987 field experiments (cf. chapter 3) were used to derive yield-water use (irrigation or ET) relations for corn, sorghum and peanut, respectively. Stewart et al. model (1977) was used to estimate maximum transpiration from maximum ET data of those crops and de Wit's m factor was calculated. On the other hand, pure stands of sorghum and peanut were compared to the mixture of those two crops using the traditional LER concept. By analogy with the area-time equivalency ratio, a similar analysis was introduced by integrating the amount of water used to the LER calculations. This was justified by the difference in maturing times of sorghum and peanut (102 vs. 134 days in 1986; 102 to 126 vs. 160 to 203 days in 1987) which required significantly greater seasonal water inputs in the latter crop. The removal of sorghum from intercrop plots at physiological maturity resulted in a reduction in canopy ground cover and an apparent increase in the amount of water lost by evaporation, thereby decreasing the water-use efficiency. A biological efficiency index accounting for both the land area and the seasonal amount of water used was defined as follows:

$$\mathrm{TLWUER} = \frac{Y_{is} \,.\, W_{ss}}{Y_{ss} \,.\, W_{sp}} + \frac{Y_{ip} \,.\, W_{pp}}{Y_{pp} \,.\, W_{sp}} \qquad [49]$$

where TLWUER is the total land-water use equivalency ratio, Y_{is} and Y_{ss} are sorghum yields, Y_{ip} and Y_{pp} are peanut yields in intercrop and pure stands, respectively; W_{ss}, W_{pp} and W_{sp} are the seasonal water use (irrigation or ET) for sole sorghum, sole peanut and sorghum-peanut intercrop, respectively. It is worth noting that TLWUER implicitly includes a time factor through its water-use component.

On another perspective, sole crop yields based on the LER concept (Eq. [46] and [47]) were calculated and conjugate water production functions (sorghum-water use and peanut-water use) were derived for "equivalent" pure stands and intercrop, respectively.

Finally, all the grain yield data from all water treatments for the two seasons were pooled and an overall mean yield was calculated for each crop or cropping system in order to assess yield stability. The system with the most stable yield would be the one which exhibits the least yield variation.

Results and Discussion

Corn

Biological and agronomic yields of corn as well as the respective seasonal irrigation and evapotranspiration are summarized in Table 11 for the four water managements. Yields in the well-irrigated treatment were 23427 and 11337 kg/ha for the above ground dry matter and grain yield (reported at 15.5% water content by weight), respectively.

Corn water production functions depicted in figure 23 show strong linear relationships between dry matter (above ground dry matter) and seasonal ET (R^2 = 0.995) or irrigation amount (R^2 = 0.990). Similar regression functions (Fig. 24) were found using grain yield (R^2 = 0.989 and R^2 = 0.988, respectively). Irrigation production functions exhibited smaller slopes than ET functions. The ratios of the two slopes were 0.815 and 0.816 for dry matter and grain yield functions, respectively. These ratios can be used as a measure of the irrigation-use efficiency (Stewart and Hagan, 1973; Stegman et al., 1980; Hammond et al., 1981b). A ratio of 1.0 would mean that all irrigation water was effectively used to increase actual ET, thereby

Table 11. Yield of Pioneer 3165 corn subjected to four water managements, Gainesville, 1987.

Water management	Irrigation cm	AET cm	Corn yield[†] Dry matter kg/ha	Grain[‡] kg/ha
1-Irrigation, optimum:	40.35	58.85	23427 (1058)	11337 (494)
2-Irrigation, stress on sorghum:	28.25	52.74	18615 (1396)	8035 (999)
3-Irrigation, stress on peanut:	23.71	46.57	15708 (3039)	6504 (2021)
4-Rainfed:	9.95	34.82	8021 (2203)	1018 (746)

[†] Standard deviation in parentheses.

[‡] Grain yield reported at 15.5% water content by weight.

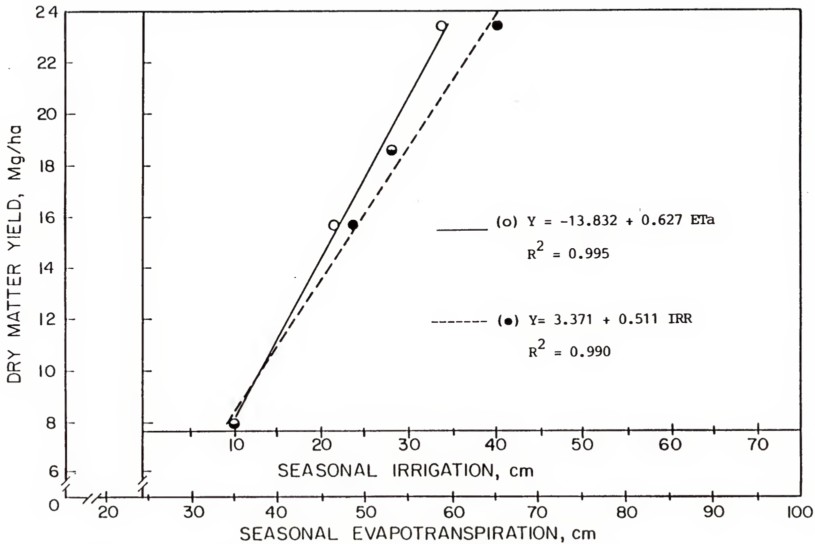


Fig. 23. Pioneer Brand 3165 corn aboveground dry matter yield versus seasonal irrigation or evapotranspiration, 1987, IREP.

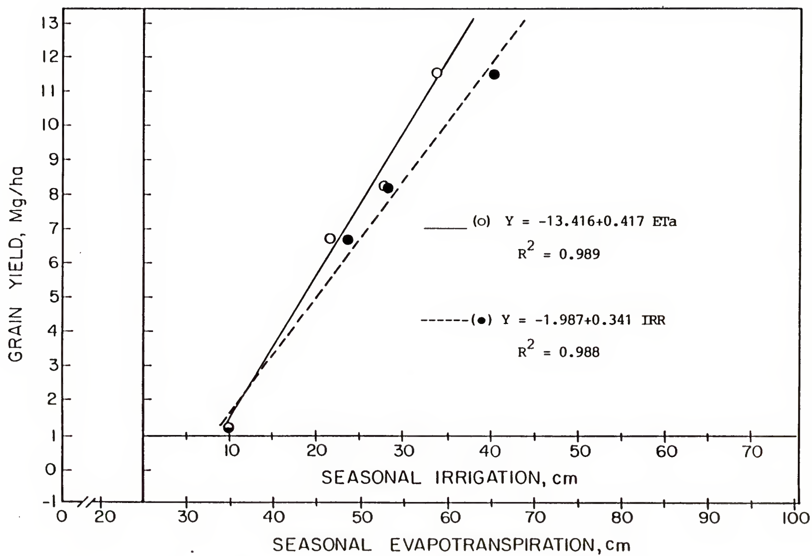


Fig. 24. Pioneer Brand 3165 corn grain yield versus seasonal irrigation or evapotranspiration, 1987, IREP.

improving production. Such value represents quite an ideal situation. In the present experiment, about 82% of irrigation water applied contributed to ET increase in corn. That percentage is rather satisfactory given the erratic rainfall pattern in Gainesville during the growing season, coupled with the high susceptibility to drainage of the soil in the experimental site. One of the objectives in water management is to obtain a slope of the irrigation production function as near that of the ET function as possible. Usually, as irrigation amounts increase, the irrigation function tends to depart from linearity and typically curves away from the ET function. Such curvilinear relationships are indicative of excessive loss of water by deep drainage or runoff and were not observed in this experiment with corn.

Figure 25 illustrates a plot of relative above ground dry matter as a function of relative seasonal ET. The regression line provided a way for estimating maximum transpiration from maximum ET according to Eq. [41]. These values were then used to estimate the m factor according to Eq. [42]. The computed m value was equal to 192 $kg.ha^{-1}.day^{-1}$ and compares very well with the 183 $kg.ha^{-1}.day^{-1}$ reported by Fischer and Turner (1978) for the above ground yield of corn in Mandan (N. Dakota). A similar calculation could be done using marketable yield in place of dry matter.

A plot of relative grain yield reduction (1 - Ya/Ymax) versus relative ET deficit (1 - ETa/ETmax) is depicted in figure 26. The slope of this relationship is equal to Ky = 2.167. The Ky gives the unit of relative grain yield reduction per unit of relative ET deficit and is called yield response factor (after Doorenbos and Kassam, 1979). A slope of 1.0 (1:1 line) would indicate that grain yield is reduced in response to soil water deficit in the same proportions as seasonal ET deficit. The observed Ky value illustrates that grain yield declines 2.167 times as fast as ET reduction. The dashed

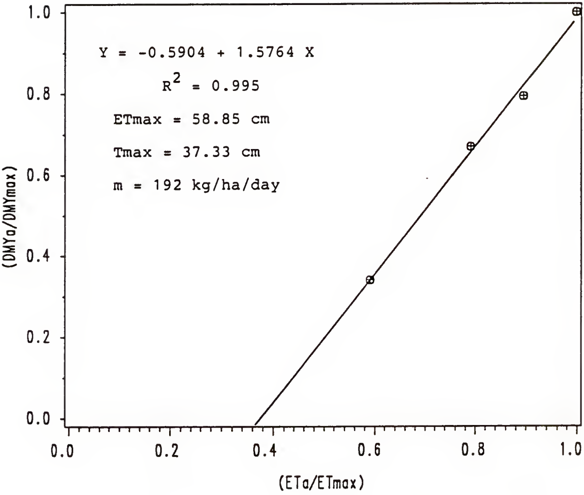


Fig. 25. Pioneer Brand 3165 corn relative dry matter yield versus relative seasonal evapotranspiration, 1987, IREP.

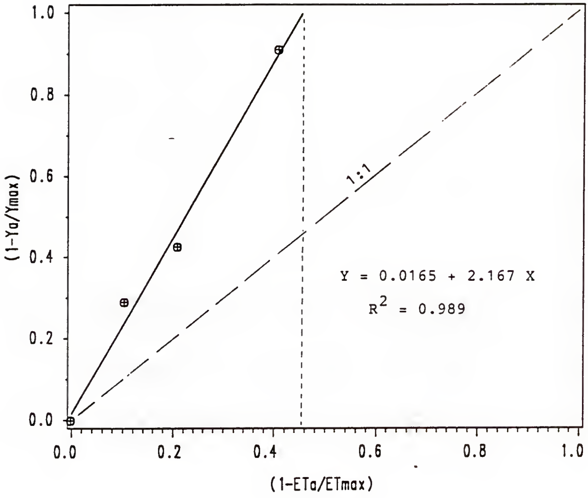


Fig. 26. Pioneer Brand 3165 corn relative grain yield reduction versus relative evapotranspiration deficit, 1987.

vertical line on figure 26 indicates the value of ET deficit at which grain yield would be expected to become nil:

$$1 - Ya/Ymax = 0.0165 + 2.167 \quad (1 - \frac{ETa}{ETmax})$$

if Ya = 0 then ETa = 0.546 ETmax.

Thus a reduction of ET to 54.6% (or an ET deficit of 45.4%) of the observed maximum ET (measured in water management 1) would result in zero grain yield. A similar analysis can be done using biological yield in place of marketable yield. But one should keep in mind the inherent limitations of such analyses which cannot be directly extrapolated to other environmental conditions. The timing of the water stress, in particular, has been recognized to be at least as important as the seasonal ET deficit. Barnes and Wooley (1969) reported grain yield reductions of 6% when water stress was imposed on maize only at tassel emergence, 73% when imposed at silking-pollination only, and 48% when imposed at blister kernel stage only. Denmead and Shaw (1960) found grain yield reductions of 25% at vegetative stage, 50% at silking and 21% during ear development.

The β_0 parameter in the Stewart model (Eq. 41), and the yield response factor Ky, can both be calculated from the ET production functions. It can be shown that

$$\beta_0 = b_1 \quad (ETmax/Ymax_1)$$

similarly, $$Ky = b_2 \quad (ETmax/Ymax_2)$$

where b_1 and b_2 are the slopes of the ET production functions for dry matter and grain

yield, respectively; $Ymax_1$ and $Ymax_2$ are the maximum dry matter and grain yields, respectively; and ETmax is the maximum seasonal ET.

Pioneer Brand 3165 has been identified to be more water stress tolerant than some other corn hybrids grown in Florida (Lorens et al., 1987a and 1987b). The irrigation water-use efficiency found in the present study (341 kg grain ha^{-1} cm^{-1}) is the same as the 342 kg grain ha^{-1} cm^{-1} reported by Riestra-Diaz (1984) for the McCurdy 84AA corn hybrid grown under nitrogen-sufficient conditions on the same site in 1982. The evapotranspiration WUE was lower than that reported by Riestra-Diaz (417 vs. 457 kg grain ha^{-1} cm^{-1}) but was much higher than the WUE under nitrogen-stressed conditions from the same author (248 kg ha^{-1} cm^{-1}). Continuing the comparison with the McCurdy 84AA, Pioneer Brand 3165 corn had a higher yield response factor Ky (2.17 vs. 1.72) showing a greater rate of decline in grain yield with decreasing ET. Thus, as far as grain yield is concerned, Pioneer 3165 may not present any exceptional water-stress tolerance characteristics. Further field investigations would be necessary for a better understanding of its water relations.

Sorghum

Sorghum yields and seasonal water use are summarized in Tables 12 and 13 for the 1986 and 1987 experiments, respectively. Both tables report data for Northrup King Savanna 5 grain sorghum hybrid grown in pure stand and in mixture with peanut; only sole sorghum will be discussed in this section. The higher maximum yield levels observed in 1987 are consistent with previous data reported in the region and may be due to the early planting (13 April in 1987 vs. 20 June in 1986) for which the peak

Table 12. Yield of Northrup King Savanna 5 grain sorghum subjected to three water managements and two cropping systems, Gainesville, 1986.

Water management and crop. syst.	Irrigation cm	AET cm	Sorghum yield[1] Dry matter kg/ha	Grain[§] kg/ha
1-Irrigation,				
optimum: -sole crop	23.85	40.97	16777 (702)	6252 (485)
-intercrop	23.85	42.56	15481 (785)	6270 (290)
2-Irrigation,				
stress on sorghum				
-sole crop	11.65	41.99	15757 (1667)	6357 (279)
-intercrop	11.65	42.23	15075 (405)	6110 (319)
3-Rainfed				
-sole crop	4.65	38.29	14677 (1738)	6316 (224)
-intercrop	4.65	39.67	13118 (2866)	5742 (977)

[1] Standard deviation in parentheses.
[§] Grain yield reported at 13% water content by weight.

Table 13. Yield of Northrup King Savanna 5 grain sorghum subjected to four water managements and two cropping systems, Gainesville, 1987.

Water management and crop. syst.	Irrigation cm	AET cm	Sorghum yield[1] Dry matter kg/ha	Grain[§] kg/ha
1-Irrigation,				
optimum: -sole crop	36.76	41.87	16898 (639)	8029 (415)
-intercrop	36.76	43.22	13283 (743)	6263 (575)
2-Irrigation,				
stress on sorghum:				
-sole crop	24.06	38.21	17182 (1590)	7143 (344)
-intercrop	24.06	39.22	11045 (1102)	4985 (638)
3-Irrigation,				
stress on peanut:				
-sole crop	23.71	45.81	13547 (1956)	4576 (1008)
-intercrop	23.71	45.51	10254 (2311)	4043 (1543)
4-Rainfed:				
-sole crop	9.95	37.93	11719 (1476)	3550 (632)
-intercrop	9.95	38.21	8003 (1013)	2713 (448)

[1] Standard deviation in parentheses.
[§] Grain yield reported at 13% water content by weight.

growth periods of the crop coincide with the high solar radiations of the months of June and July, as well as to less incidence of insect damage.

Based on above-ground dry matter production, sorghum responded poorly to irrigation in 1986; grain yield did not respond at all. This situation can be explained by the fairly well distributed rainfall events throughout the growing season. The relative seasonal ET deficit in the rainfed treatment (treatment 3) was only 6.54% of the measured maximum ET. That ET deficit resulted in a 12.52% reduction in total dry matter produced, but did not affect grain yield which was even slightly higher in treatments 2 and 3 than in the optimum treatment. The minor soil water deficits observed in treatments 2 and 3 occurred around 50 DAP and during the late grain filling period. The resulting water stress may not have coincided with sensitive growth stages of the sorghum crop. Shipley and Regier (1970), Hiler and Clark (1971), using the stress day index concept suggested that sorghum grain yield is reduced by only 12% when the water stress occurs at six to eight-leaf stage, 36% at mid to late boot and 45% at heading and flowering. Moreover, excessively wet conditions during the late grain filling period in 1986 favored kernel rotting in treatment 1, thereby decreasing seed quality and harvestable yield.

In 1987, sorghum responded well to irrigation. The decrease in irrigation frequency from treatment 1 to 4 resulted in increasing crop water stress in the same order. Grain yield was more affected by the stress than total biomass. This is partly due to the fact that various degrees of water stress occurred at very sensitive growth stages of the crop (booting-flowering) in treatments 2, 3 and 4, respectively (cf. chapter 3). The resulting effect was the abortion of some of the flowers and the enhancement

of tillering as the crop recovered later from the droughty periods. The tillering increased total biomass more than it did grain yield.

The data in Table 13 reflect differences in harvest dates (see Page 82 in Chapter 3), and treatments 3 and 4 are not suitable for production function estimation in combination with treatments 1 and 2. Nevertheless, an exploratory regression analysis was made based solely on the following observation. During the 19-day extended season (treatments 3 and 4) new panicles matured and old ones lost seed to mildew and rot. Thus, the assumption was made that gain equalled loss so that final yields were about equal to those which would have been harvested at the 107-day harvest of treatment 2. On this basis, adjusted seasonal irrigation and ET values became, respectively, 19.49 and 36.97 cm for treatment 3, and 9.95 and 30.37 cm for treatment 4. Figures 27 and 28 show the regression results.

The regression functions based on total above ground dry matter yield were not significant at $p = 0.05$ and not even at $p = 0.10$. Only the grain-water use regression lines were significant ($p = 0.10$). It should be noted that both the dry matter-irrigation and dry matter-ET regressions were poor. This can be attributed not only to uncertainties about treatments 3 and 4, but to the lack of a strong positive response of treatment 1 over treatment 2. Apparently, using the corn water requirement as the basis for scheduling irrigation of sorghum resulted in an over-irrigation of the latter, especially late in the season. The irrigation function data points in figures 27 and 28 depict the typical curving away from the ET function with increasing irrigation, characteristic of excessive water loss by deep drainage. The ratio of the respective slopes of the irrigation and and ET production functions for grain was 0.445, meaning that only 44.5% of applied irrigation was used in increasing sorghum ET.

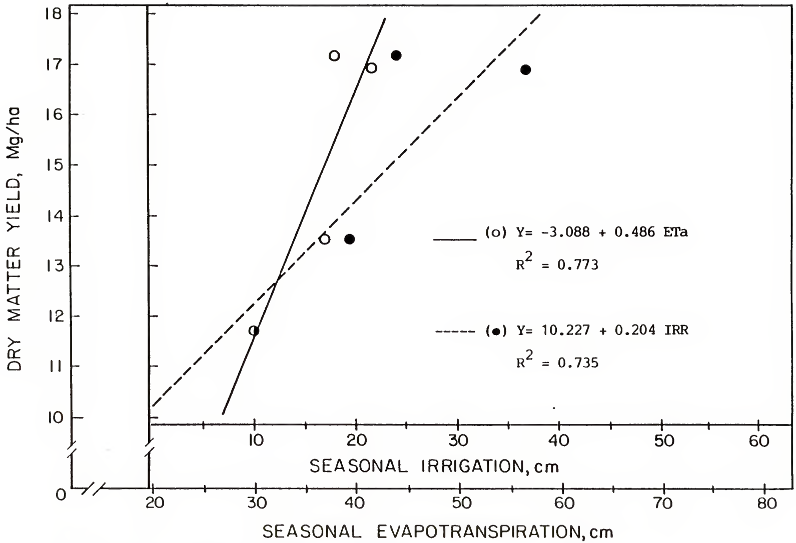


Fig. 27 Northrup King Savanna 5 sorghum dry matter yield versus seasonal irrigation or evapotranspiration, 1987.

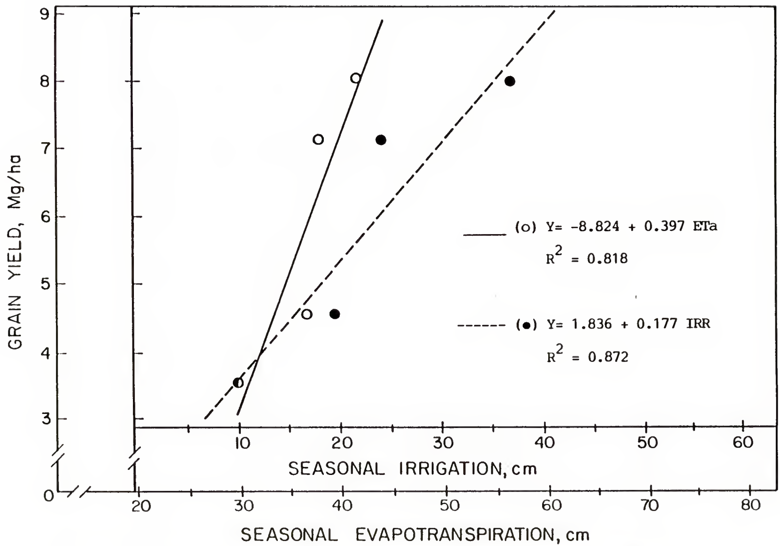


Fig. 28. Northrup King Savanna 5 sorghum grain yield versus seasonal irrigation or evapotranspiration, 1987.

Figure 29 illustrates the plot of relative above ground dry matter versus relative evapotranspiration. Stewart and coworkers' model was used as previously with corn to estimate maximum transpiration and the de Wit m factor. A value of 168 kg ha^{-1} cm^{-1} was found and appears to be lower than the 192 value for corn.

Figure 30 depicts the relative grain yield reduction as a function of the relative ET deficit in the sorghum crop in 1987. The yield response factor Ky is equal to 2.073 and is slightly lower than for the maize crop. The predicted critical seasonal ET value at which grain yield would be nil is ETa = 0.53 ETmax.

Peanut

Table 14 summarizes the seasonal irrigation, ET, total dry matter, pod and grain yields of Florunner peanut for the three water managements and two cropping systems. Only sole cropping data will be discussed in this section. Treatment 1 exhibited slightly higher pod and grain yields than the stressed treatments. But none of the yield components responded significantly to irrigation for the reasons already given in the previous section on sorghum. Optimum irrigation treatment (treatment 1) had a higher percentage of pods and grain remaining in the soil at harvest (drops) than the water-stressed treatments. The removal of that percentage from the reported grain yield in table 14 would give about equal harvestable yields for all three water managements. Data for the Southern Runner peanut are given in table 15. The crop was harvested twice, at 160 and then at 203 days. Significant yield increases were obtained by delayed harvest. Mean values for the first harvest were based on four replications per treatment, whereas in the second harvest the number of replicates was three for treatment 1, two for treatment 2, and four for treatments 3 and 4, respectively. The relatively low values of yields for treatment 2 in the second harvest may be due

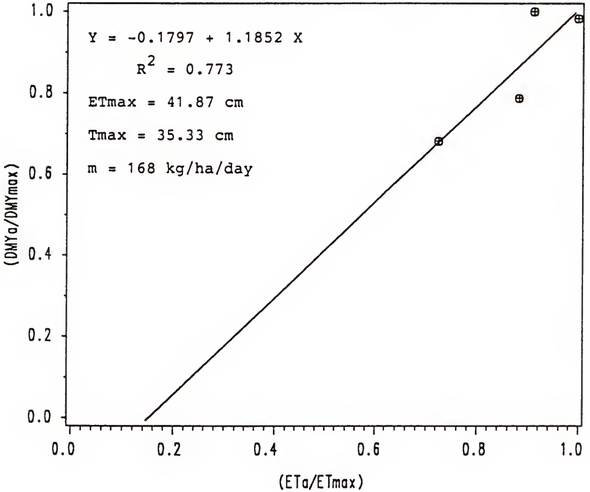


Fig. 29. Northrup King Savanna 5 sorghum relative dry matter yield versus relative evapotranspiration, 1987.

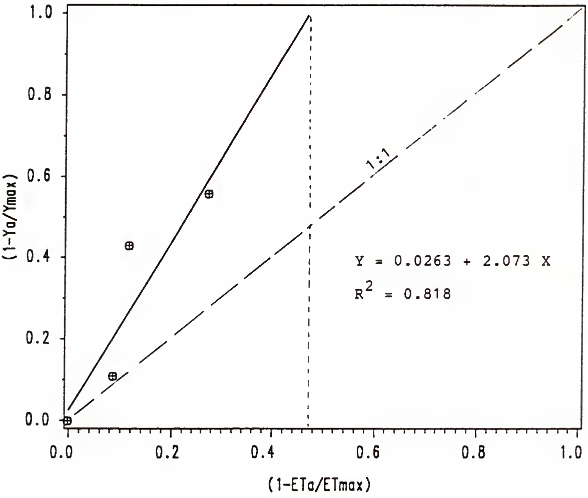


Fig. 30. Northrup King Savanna 5 sorghum relative grain yield reduction versus relative evapotranspiration deficit, 1987.

Table 14. Yield of Florunner peanut subjected to three water managements and two cropping systems, Gainesville, 1986.

Water management and crop. syst.		Irrigation cm	AET cm	Peanut yield[¶] Dry matter kg/ha	Pod kg/ha
1-Irrigation, optimum:	-sole crop	30.85	43.43	11957 (571)	6083 (425)
	-intercrop	30.85	41.78	1082 (409)	190 (101)
2-Irrigation, stress on sorghum:	-sole crop	13.65	42.81	11448 (1279)	5695 (580)
	-intercrop	13.65	40.54	1277 (158)	290 (34)
3-Rainfed:	-sole crop	4.65	40.46	12594 (1075)	5819 (378)
	-intercrop	4.65	38.77	1957 (426)	566 (231)

		Grain[§] kg/ha	Drops kg/ha
1-Irrigation, optimum:	-sole crop	5040 (362)	666
	-intercrop	133 (99)	13
2-Irrigation, stress on sorghum:	-sole crop	4678 (488)	423
	-intercrop	206 (16)	8
3-Rainfed:	-sole crop	4735 (293)	229
	-intercrop	402 (222)	12

[¶] Standard deviation in parentheses.

[§] Grain yield reported at 7% water content by weight.

Table 15. Yield of Southern Runner peanut subjected to four water managements and two cropping systems, Gainesville, 1987.

Water management and crop. syst.	Irrigation cm	AET cm	Peanut yield[¶] Dry matter kg/ha	Pod kg/ha
1-Irrigation, optimum:				
-sole (160 DAP)	48.15	53.61	13513 (897)	5710 (738)
-sole (203 DAP)	51.15	61.70	18188 (3379)	8633 (2442)
-inter (160 DAP)	48.15	60.78	6662 (1585)	2821 (202)
-inter (203 DAP)	51.15	69.18	9623 (728)	4510 (182)
2-Irrigation, stress on sorghum:				
-sole (160 DAP)	34.51	54.87	13900 (1909)	6243 (805)
-sole (203 DAP)	37.51	63.20	15502 (2348)	8405 (385)
-inter (160 DAP)	34.51	60.05	5791 (702)	2136 (369)
-inter (203 DAP)	37.51	67.81	8467 (384)	4725 (157)
3-Irrigation, stress on peanut:				
-sole (160 DAP)	27.95	52.60	12420 (1817)	5986 (564)
-sole (203 DAP)	30.95	60.40	16423 (3898)	8645 (2047)
-inter (160 DAP)	27.95	55.46	4754 (1068)	1710 (339)
-inter (203 DAP)	30.95	62.65	7934 (1658)	4469 (579)
4-Rainfed:				
-sole (160 DAP)	9.95	42.30	9865 (922)	3631 (396)
-sole (203 DAP)	12.95	49.80	10311 (1312)	5238 (1191)
-inter (160 DAP)	9.95	42.42	3943 (619)	1005 (176)
-inter (203 DAP)	12.95	50.64	4575 (815)	1535 (432)

Table 15--continued

Water management and crop.syst.	Grain[§] kg/ha	Drops kg/ha
1-Irrigation, optimum:		
-sole (160 DAP)	4505 (539)	685
-sole (203 DAP)	6538 (1782)	1268
-inter (160 DAP)	1947 (142)	68
-inter (203 DAP)	3265 (149)	418
2-Irrigation, stress on sorghum:		
-sole (160 DAP)	4919 (610)	556
-sole (203 DAP)	6473 (531)	1171
-inter (160 DAP)	1395 (239)	43
-inter (203 DAP)	3243 (8)	246
3-Irrigation, stress on peanut:		
-sole (160 DAP)	4582 (439)	357
-sole (203 DAP)	6449 (1726)	864
-inter (160 DAP)	1058 (157)	32
-inter (203 DAP)	2967 (229)	451
4-Rainfed:		
-sole (160 DAP)	2754 (308)	217
-sole (203 DAP)	3762 (825)	395
-inter (160 DAP)	667 (117)	15
-inter (203 DAP)	1005 (303)	67

[¶] Standard deviation in parentheses.
[§] Grain yield reported at 7% water content by weight.

to the small number of replicates since that treatment was the best in the first harvest. Another important remark is that the first harvest consisted of a 4.8 m^2 sample per plot whereas the sampled area was only 1.2 m^2 in the second harvest.

The observed pod and grain yield increases from harvest 1 to 2 are probably due to the indeterminate growth habit of Southern Runner cultivar coupled with its resistance to Cercospora leafspot. Such yield increase trends were reported by Pedelini (1988) from an experiment conducted in 1987 at Green Acres near Gainesville, under well-watered conditions. Pod yield increased steadily from the first harvest at 136 DAP to the fourth harvest at 178 DAP, then the yield declined at the last harvest at 192 DAP due to a pod rot disease that increased the amount of drops. But the highest reported pod yield at Green Acres at 178 days did not match the one obtained in the present experiment at the first harvest (160 days), probably because of a wider row spacing used in the former experiment (90 cm vs. 60 cm). Water management may have been also a key factor. The highest yield at the first harvest was obtained in treatment 2, followed by treatment 3, then treatment 1, and lastly the rainfed treatment (4). Thus, the supposed water-stressed treatments outyielded the optimum treatment in the present experiment. Treatment 1 improved its performance at the second harvest following a long droughty period of 43 days.

The amount of drops increased systematically with increasing irrigation at both harvests on one hand, and from first to second harvest on the other hand. But the latter increases did not upset the yield advantage obtained by the delayed harvest. Harvestable pod or grain yields for each treatment and harvest time can be calculated by subtracting the amount of drops from the respective yields reported in table 15.

Graphs of total dry matter or grain yield versus seasonal irrigation or ET are shown in figures 31 and 32 for the two harvests. All four regression functions were significant at $p = 0.05$ despite the low coefficients of determination for the irrigation functions. Irrigation-use efficiency was 41.7% when calculated using total dry matter, and 33.8% when using grain yield functions. Thus, the peanut crop had the lowest irrigation-use efficiency among the three crops grown in 1987. Low values were reported also by Riestra-Diaz (1984) who found an average value of 34% for 10 peanut varieties grown in similar conditions as in the present experiment. The observed low irrigation-use efficiency may be attributable to either under-estimation of actual ET by limiting the active root zone to 90 cm, or to over-irrigation, or to both. Under-estimating ET would inflate the slope of the ET function thereby pulling it away from the irrigation function. The root length density distribution measured at 82 DAP revealed that an average of 92% of the total root length was within the first 90 cm depth of the profile. The percentage represents the average value for the three water stressed treatments (2, 3 and 4) in which peanut had the deepest root system. Thus, some water must have been extracted by the peanut crop from below the 90 cm depth.

The extended growing season (from 160 to 203 days) resulted in significant increases in yields with very little additional input of water, thereby improving water-use efficiency. The crop received only 3.0 cm of water during the 43 days separating the two harvest dates. Given that when evapotranspiration is prevented an initially satiated soil profile in the experimental site would drain to about 7.2 cm of available soil water to a depth of 120 cm (or 9.0 cm to a depth of 150 cm) within three days (cf. chapter 2) it is unlikely that the supposedly deeper root zone was the only factor that helped peanut crop stay green and increase both the biomass and the grain yields

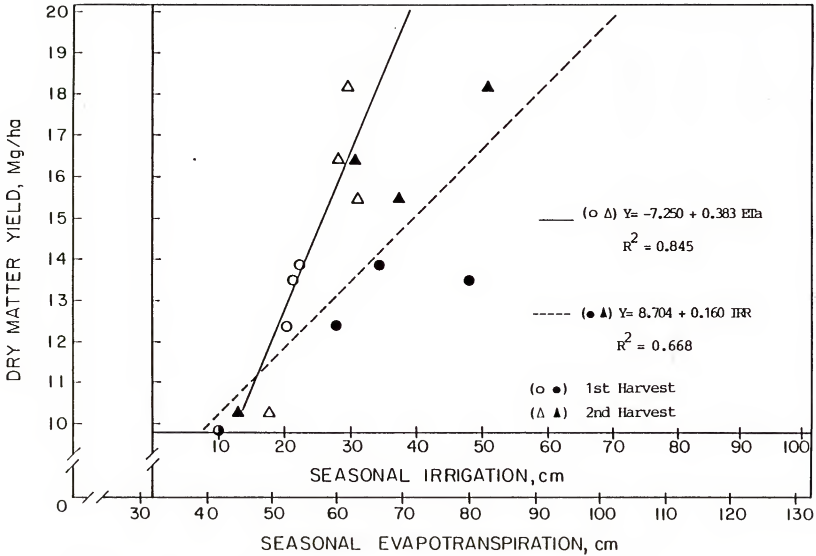


Fig. 31. Southern Runner peanut dry matter yield versus seasonal irrigation or evapotranspiration, 1987.

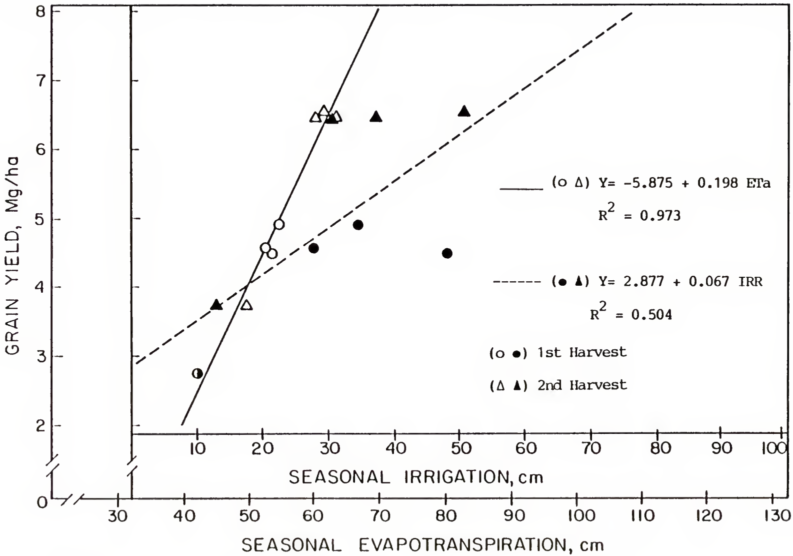


Fig. 32. Southern Runner peanut grain yield versus seasonal irrigation or evapotranspiration, 1987.

during that 43-day period. A separate regression analysis using yields from each harvest gave the following water production functions:

(1) First harvest:

Pod yield = 3.652 + 0.058 IRR; R^2 = 0.591

Pod yield = - 5.011 + 0.205 ETa; R^2 = 0.973

Grain yield = 2.716 + 0.049 IRR; R^2 = 0.637

Grain yield = - 4.360 + 0.168 ETa; R^2 = 0.987

(2) Second harvest:

Pod yield = 4.774 + 0.089 IRR; R^2 = 0.725

Pod yield = - 7.834 + 0.265 ETa; R^2 = 0.938

Grain yield = 3.355 + 0.074 IRR; R^2 = 0.744

Grain yield = - 7.120 + 0.220 ETa; R^2 = 0.966

where yield is expressed in $Mg.ha^{-1}$, and irrigation and ETa in cm.

The data points for grain yields can be identified on figure 32 for the two harvests. The first harvest shows a leveling off, then a decline in grain yield as irrigation amount increases. Data for the second harvest also show a plateauing of grain yield with increasing irrigation typical of over-irrigation conditions resulting in excessive loss of water by deep drainage.

The above sets of equations show that from first to second harvest, irrigation WUE was increased by 53.45% based on pod yields (or by 51.02% based on grain yields). The corresponding increase in ET water use efficiency was 29.27% (30.95% based on grain yields). Such field water-use efficiency increases may be explained by the high mesophyll resistance of peanut which tends to reduce transpiration more than net photosynthesis as a result of partial stomatal closure during water stress.

The irrigation regression coefficient of 0.058 Mg pod ha^{-1} cm^{-1} of the first harvest is about the same as the 0.057 value reported by Riestra-Diaz in the study referenced earlier (1984), but the ET coefficient of 0.205 Mg pod ha^{-1} cm^{-1} is much higher than the 0.166 value obtained by Riestra-Diaz, or the 0.162 value reported by Hammond et al. (1981b).

Figure 33 represents a plot of relative dry matter yield versus relative ET. Using the slope of the regression (Stewart et al. 1977), maximum transpiration was estimated and the de Wit m factor calculated (m = 90 kg ha^{-1} day^{-1}). Figure 34 depicts the relative grain yield reduction vs. relative ET deficit for the 1987 peanut crop. The calculated yield response factor was 1.918 and the critical actual ET which would result in a zero grain yield was found to be equal to ETa = 0.468 ETmax where ETmax represents the measured maximum ET in the well-irrigated treatment. Evapotranspiration had to be decreased more in peanut than in sorghum and lastly corn to reach the zero grain yield point. Conversely, the respective values of the m factor for the three crops show that the two grasses were about twofold as water-use efficient as peanut.

Sorghum-Peanut Intercrop

Sorghum-peanut intercrop was compared to sole crops on the basis of their respective biological efficiencies, water-use efficiencies, and yield stability.

Biological efficiency indices of intercrop system

In order to assess any yield advantages of intercrop over sole crops, biological efficiency indices of the sorghum-peanut mixture were calculated using the yields and water use amounts of tables 12 through 15 and according to Eq. [45] and [49]. The total land equivalent ratio (TLER) and total land water-use equivalency ratio (TLWUER) data for the 1986 experiment are summarized in table 16 for the three

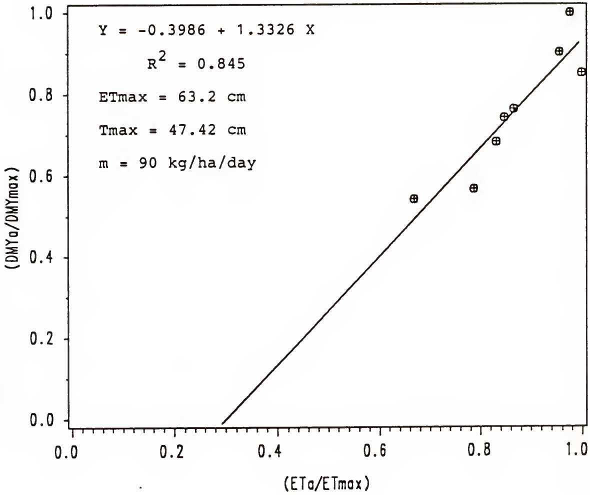


Fig. 33. Southern Runner peanut relative dry matter yield versus relative evapotranspiration, 1987.

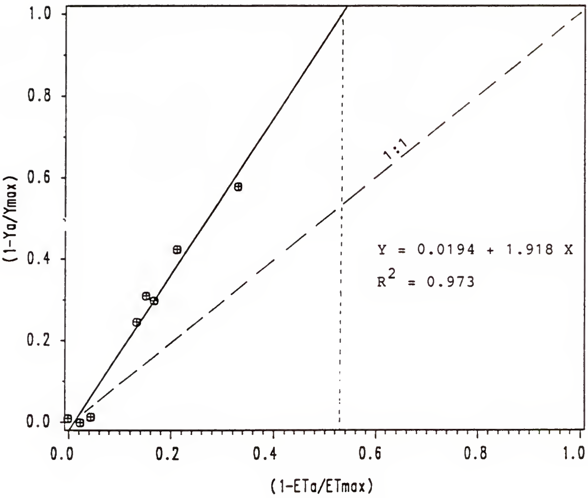


Fig. 34. Southern Runner peanut relative grain yield reduction versus relative evapotranspiration deficit, 1987.

Table 16. Biological efficiency indices for the sorghum-peanut intercrop, 1986.

Water management and crop	Dry matter[1] LER	Dry matter[1] LWUER Irrigation	Dry matter[1] LWUER ETa
1-Irrigation, optimum:			
-sorghum	0.92	0.71	0.90
-peanut	0.09	0.09	0.09
	1.01 (0.04)	0.80 (0.04)	1.00 (0.04)
2-Irrigation, stress on sorghum:			
-sorghum	0.96	0.82	1.00
-peanut	0.11	0.12	0.12
	1.07 (0.02)	0.94 (0.07)	1.12 (0.08)
3-Rainfed:			
-sorghum	0.89	0.89	0.88
-peanut	0.16	0.16	0.16
	1.05 (0.07)	1.05 (0.06)	1.04 (0.05)

Water management and crop	Grain LER	Grain LWUER Irrigation	Grain LWUER ETa
1-Irrigation, optimum:			
-sorghum	1.01	0.78	0.99
-peanut	0.03	0.03	0.03
	1.04 (0.02)	0.81 (0.06)	1.02 (0.08)
2-Irrigation, stress on sorghum:			
-sorghum	0.96	0.82	1.00
-peanut	0.04	0.04	0.05
	1.00 (0.04)	0.86 (0.04)	1.05 (0.05)
3-Rainfed:			
-sorghum	0.91	0.91	0.90
-peanut	0.09	0.09	0.09
	1.00 (0.11)	1.00 (0.11)	0.99 (0.11)

[1] Standard deviation in parentheses.

water managements. Based on TLER values, no dry matter or grain yield advantage was found between intercropping and sole cropping. Total LER values were not significantly different from 1.0 in all treatments. Average TLWUER based on irrigation amounts were less than 1.0 in treatments 1 and 2 and equal to 1.04 in the rainfed treatment. Total LWUER based on actual ET were not different from 1.0, except in treatment 2 where it was equal to 1.12 suggesting a 12% dry matter yield advantage of intercrop.

Table 17 gives average LER and LWUER values for the 1987 experiment. Based on the land equivalent ratio concept, intercropping exhibited both biomass and grain yield advantages over sole cropping. The observed advantages increased with the amount of water applied as well as with time. For the second peanut harvest, total LER values varied from 1.15 in the rainfed to 1.36 in the optimum irrigation treatment, suggesting yield advantages of 15 to 36% over sole cropping. These yield advantages are partly to totally upset when using the LWUER concept based either on seasonal irrigation or on seasonal ET. The above results are not in total agreement with those of Natarajan and Willey (1986), Harris et al. (1987), or Harris and Natarajan (1987). These authors found that intercrops of sorghum and peanut achieved greater relative yield advantages under drought than under well-watered conditions, suggesting that the mixture may combine both temporal and spatial complementarities, thereby resulting in larger yield benefits. Only the second part of their assertion was confirmed in the present study. In 1986, peanuts were harvested 32 days after sorghum in both intercrop and pure stand. This did not allow peanut enough time to catch up or recover from the early stress imposed by the tall and highly competitive sorghum crop. As a consequence, there was no significant yield advantage of intercrop. In 1987, there

Table 17. Biological efficiency indices for the sorghum-peanut intercrop (2nd peanut harvest), 1987.

Water management and crop	Dry matter[1]		
	LER	LWUER	
		Irrigation	ETa
1-Irrigation, optimum:			
-sorghum	0.81	0.58	0.49
-peanut	0.54	0.54	0.48
	1.35 (0.09)	1.12 (0.08)	0.97 (0.07)
2-Irrigation, stress on sorghum:			
-sorghum	0.65	0.42	0.37
-peanut	0.55	0.55	0.52
	1.20 (0.02)	0.97 (0.04)	0.89 (0.04)
3-Irrigation, stress on peanut:			
-sorghum	0.76	0.58	0.55
-peanut	0.49	0.49	0.47
	1.25 (0.05)	1.07 (0.03)	1.02 (0.03)
4-Rainfed:			
-sorghum	0.69	0.53	0.52
-peanut	0.45	0.45	0.44
	1.14 (0.12)	0.98 (0.11)	0.96 (0.11)

Table 17--continued

Water management and crop	Grain[1] LER	LWUER Irrigation	LWUER ETa
1-Irrigation, optimum:			
-sorghum	0.83	0.59	0.50
-peanut	0.53	0.53	0.47
	1.36 (0.16)	1.12 (0.15)	0.97 (0.13)
2-Irrigation, stress on sorghum:			
-sorghum	0.69	0.44	0.39
-peanut	0.50	0.50	0.47
	1.19 (0.06)	0.94 (0.03)	0.86 (0.03)
3-Irrigation, stress on peanut:			
-sorghum	0.87	0.67	0.64
-peanut	0.49	0.49	0.47
	1.36 (0.09)	1.16 (0.06)	1.11 (0.06)
4-Rainfed:			
-sorghum	0.78	0.60	0.59
-peanut	0.36	0.36	0.36
	1.14 (0.18)	0.96 (0.15)	0.95 (0.15)

[1] Standard deviation in parentheses.

Table 18. Stability of yields of sorghum and peanut in sole cropping, intercropping, and "equivalent sole" cropping systems, based on coefficients of variation of grain yields averaged over all water managements (1986-1987).

	Sole cropping		Intercropping			Equivalent sole		
	S	P	S	P	Total	S	P	Total
Yield (kg/ha)	5956	4831	4894	1385	628	4429	1180	5609
SE (kg/ha)	252	205	244	171	292	228	132	218
CV (%)	28.05	27.25	32.00	78.96	29.81	32.93	71.64	24.85

was an improvement in LER from first to second peanut harvest which occurred 58 and 101 days, respectively, after the removal of sorghum from intercrop in treatment 1. The corresponding time frames were 53 and 96 days in treatment 2, 34 and 77 days in treatments 3 and 4. The increased LER with time illustrates the temporal complementarity of the sorghum-peanut system. On the other hand, measured ET values were slightly higher in intercropping than in corresponding sole cropping, thereby providing evidence that intercrop can result in a better spatial use of water resources. Consequently, all other conditions being equal, crops in the intercrop plots were under more water stress than their counterparts in pure stands. This probably explains why yield advantages were greater with increasing soil water availability in the 1987 experiment.

Water-use efficiency of intercrop system

In order to compare water-use efficiency of intercrop to that of sole crops, there was a need to convert LER values into absolute yields using Eq. [46] and [47]. The resulting absolute yields of the "equivalent sole system" are compared to intercrop system in figure 35 for the 1986 experiment and figures 36a and b for the two peanut harvests in 1987. Each vertical bar represents the sum of peanut grain yield and sorghum grain yield in Mg ha^{-1} for the respective water managements and cropping systems. Also indicated on top of each bar of intercrop are the TLER values. Comparing graphs 35 and 36 reveals a contradictory trend of peanut crop. In 1986, the competitive ability of peanut decreased with increasing irrigation whereas it increased in 1987. This may be explained by the difference in the layout between the two experiments. The allocation of a greater land area to peanut in 1987 (54% compared to 50% in 1986) helped them improve their competitive ability at the expense

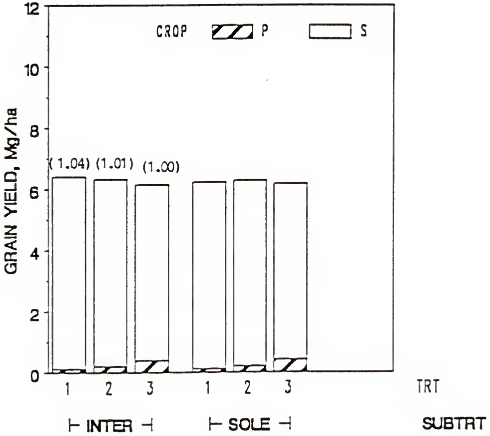


Fig. 35. Grain yields of peanut-sorghum intercrop and of its "equivalent sole system," 1986.

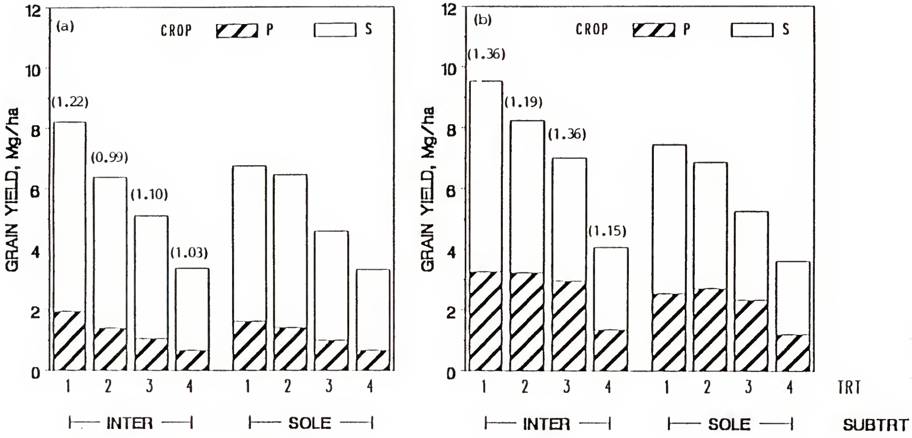


Fig. 36. Grain yields of peanut-sorghum intercrop and of its "equivalent sole system," 1987.
(a) first peanut harvest
(b) second peanut harvest

of sorghum at favorable soil-water conditions. This also illustrates the fact that maximum yield advantages are expected to occur when the component crops of the mixture are more or less equally competitive, rather than when there is an over-dominance of one crop over the other. Thus, the yield advantage would result from some complementary use of available resources, the complementarity being greatest when each crop exerts a reasonable pressure on the said resources.

Conjugate water production functions were derived by fitting intercrop yields and their "equivalent sole crop" yields to seasonal irrigation or ET. These regression functions are depicted in figures 37 and 38 for grain yields. For intercropping system for example the conjugate production functions using seasonal irrigation are:

(2) $Y_{IP} = 0.994 + 0.0517$ (IRR) $R^2 = 0.811$

(4) $Y_{IS} = 1.365 + 0.1328$ (IRR) $R^2 = 0.940$

Thus, the irrigation water-use efficiency of the intercrop system will be equal to: 0.0517 Mg grain peanut ha^{-1} cm^{-1} + 0.1328 Mg grain sorghum ha^{-1} cm^{-1}.

Similarly, the conjugate production functions of the "equivalent sole system" are:

(1) $Y_{SP} = 0.962 + 0.0374$ (IRR) $R^2 = 0.762$

(3) $Y_{SS} = 1.391 + 0.0933$ (IRR) $R^2 = 0.812$

Despite the apparently higher slopes of Eq. (2) and (4) as compared to Eq. (1) and (3) suggesting a higher irrigation water-use efficiency of intercropping over the "equivalent sole system", no significant differences between the two sets of slopes were found using a Student test at $p = 0.05$ level of significance. A similar analysis and graphing were conducted using actual ET (figure 38) and no significant difference was found either.

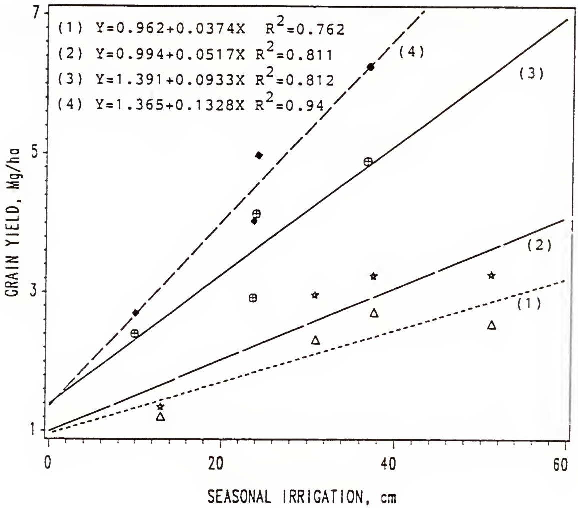


Fig. 37. Conjugate irrigation production functions of peanut-sorghum intercrop and of its "equivalent sole system," 1987.
(1) equivalent sole peanut
(2) intercrop peanut
(3) equivalent sole sorghum
(4) intercrop sorghum

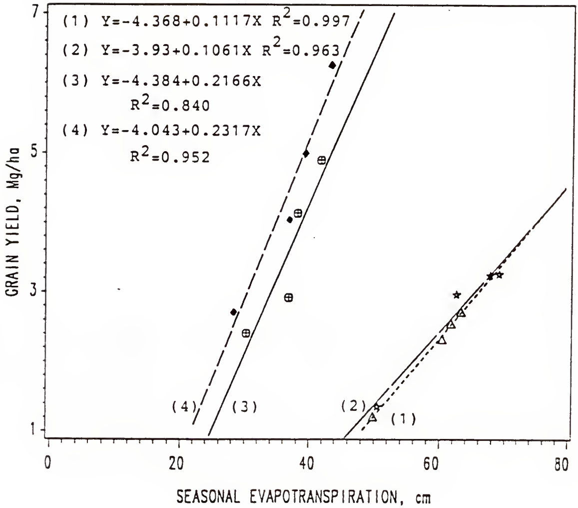


Fig. 38. Conjugate evapotranspiration production functions of peanut-sorghum intercrop and of its "equivalent sole system," 1987.
(1) equivalent sole peanut
(2) intercrop peanut
(3) equivalent sole sorghum
(4) intercrop sorghum

Yield stability

In order to assess yield stability of intercrop and sole crops over different water managements during the two growing seasons, grain yields of each crop for each cropping system were averaged over all treatments and experiments. Table 18 (page 188) summarizes the calculated average grain yields as well as the standard error of the mean and the coefficient of variation. Each individual mean was based on 44 observations. On the basis of the coefficient of variation, "equivalent sole system" exhibited the highest overall yield stability (lowest cv = 24.85%), followed by sole peanut (cv = 27.25%), sole sorghum (cv = 28.05%) and lastly intercrop (cv = 29.81%). The component crops experienced more variability than the cropping system as a whole, thereby illustrating some compensation effects of mixed cropping on yield.

Summary and Conclusions

In two field experiments conducted in 1986 and 1987, sorghum, peanut, and corn were subjected to various water management strategies with the objective of deriving yield-water use relationships of these crops grown in pure stands or in mixtures (sorghum-peanut). Irrigation was scheduled on a daily basis using tensiometers and visible signs of wilting on plant leaves. Water was applied to the optimum treatment in frequent, but small amounts (ranging between 0.6 cm per application at planting and 2.1 cm at mid and late season) in order to maintain the soil matric potential at - 200 millibars or higher at 15 and 30 cm depths throughout the growing season. The other two irrigated treatments allowed two days of visible stress symptoms (leaf wilting) during the early afternoon hours on sorghum, or on peanut. Water was also applied in same small amounts per application as in the optimum

treatment, but less frequently. The stress periods and magnitudes in the rainfed treatment occurred naturally, in line with rainfall distribution patterns. All treatments were equally irrigated during the early growth stage to ensure proper crop establishment. Irrigation application rates varied between 1.8 cm per hour along the plot edges and 3.0 cm per hour in the center. Soil water budgets were calculated throughout the growing season.

In 1986, sorghum and peanut did not respond significantly to irrigation. This was attributable to fairly well distributed rainfalls throughout their growth cycles. Conversely, all the crops grown in 1987 (sorghum, peanut and corn) experienced more droughty conditions in the water-stressed treatments. Dry matter and grain yields of corn, sorghum, and peanut increased linearly with seasonal irrigation and ET. During the two growing seasons, yield levels in the well-irrigated treatments reached their near optimum potentials when compared with similar crops grown previously in the area. A prolonged growing season in 1987 resulted in very high yields of Southern Runner peanut due mainly to the combined effects of its indeterminate growth habit, its resistance to Cercospora leafspot, and good water and crop managements.

It appears that yields of the three crops were affected differently by water stress as reflected in their respective water production functions. Corn grain yield was the most affected by soil water deficits, followed by grain sorghum and then peanut. This was probably due to the combined effects of shallower rooting habits and presumed greater physiological sensitivity of corn to drought, as compared to sorghum and peanut. Corn grain yield reductions from optimum were 29.13, 42.63, and 91.02% in treatments 2 (irrigation with stress on sorghum), 3 (irrigation with stress on peanut), and 4(rainfed), respectively. The corresponding sorghum grain yield reductions were

11.03, 43.0, and 55.79%, whereas the respective reductions for peanut were 1.0, 1.4, and 42.5%. On a different perspective, corn exhibited the highest transpirational water-use efficiency with a de Wit's m value of 192 kg of above-ground dry matter/ha/day, followed by sorghum (168 kg of above-ground dry matter/ha/day), and then peanut (90 kg of dry matter/ha/day).

Irrigation-use efficiency (ratio of the slope of the irrigation production function over the slope of the ET production function) was relatively high for corn (82%), but rather low for sorghum (45%), and for peanut (34%). The low irrigation-use efficiencies of these last two crops may be attributable to (1) over-irrigation, and (2) errors in the measurement of ET. The leveling off of yield as irrigation increased, observed with sorghum and peanut but not with corn, suggests that the former crops may have received more irrigation water (particularly in treatment 1) than needed to achieve maximum ET and yields. Thus, scheduling irrigation with several crops as subplots and irrigation as main plots did not work effectively. Furthermore, the slopes of the ET and irrigation production functions of peanut were significantly increased by purposely withholding irrigation during the late grain-filling stage, even though this was a period of no rainfall.

Sorghum-peanut association may not always be a higher yielding system than sole cropping. Yield advantages of intercropping were observed only in 1987 when the layout helped increase peanut competitiveness and the extended growing season allowed the crop to recover from the biological stress imposed by sorghum early in the season. Despite the observed yield advantages, conjugate water production functions of intercropping and of its "sole cropping equivalent" did not confer any significantly higher water-use efficiency to the mixture. The Land Water-Use Equivalency Ratio

(LWUER) concept may be another convenient way of comparing WUE of intercropping to sole cropping. Except for a few inconsistencies where LWUER values were less than unity, the conjugate water production functions and the LWUER indices were in good agreement.

It appears that, when sole crop and intercrop are both well managed, the potential yield advantages of the latter system would probably be quite limited. The highest LER values found during the two seasons were only 1.36 suggesting a 36% yield advantage. Such values contrast significantly from those sometimes reported in the literature where LER of 2.0 and greater have been found. However, the present results show that intercropping can improve productivity through the optimization of planting density and geometry, coupled with good water and crop managements. But, based on the coefficients of variation, intercropping exhibited less grain yield stability, over changing soil water managements, than sole cropping. Therefore, it appears that, in the present study intercropping failed to provide one of its most claimed advantages in low input agricultural systems. But the limited amount of data may not permit any definite conclusion on this matter.

CHAPTER 5
GENERAL CONCLUSION

Because of the limited fresh water resources on the global scale, there is a permanent need for new strategies aimed at improving on-farm water management in order to optimize both crop yield and water-use efficiency.

The strategy used in this study was to apply irrigation water in small amounts at frequent time intervals, to corn, sorghum and peanut grown in an optimum water treatment designed to obviate any yield - limiting water stress while minimizing the loss of water and soil nutrients by deep drainage below the root zone. On the other hand, timed water stresses were imposed to the aforementioned crops by delaying or withholding irrigation throughout the growing season to assess the differential effects of various soil water conditions on final yields. The scheduling of water stress was based on the combination of daily soil water potential measurements and visible signs of wilt on sorghum or peanut, respectively. The differential response of sorghum and peanut to water management was further extended to cropping systems with the objective of improving productivity through the coupling of water and crop managements.

Considering the fast draining properties of the soil in the experimental site, a preliminary hydrodynamic characterization of the soil was necessary in order to derive a field-oriented empirical model used to estimate the amount of water lost by deep percolation. By fitting data collected during an internal drainage experiment from ten selected soil profiles, satisfactory empirical relationships were found between unsaturated hydraulic conductivity K

and volumetric water content θ (or matric potential h) of the soil at selected depths in the site. Van Genuchten's model was used to fit water content versus matric potential data. The field-determined water release curves compared favorably with those obtained in the laboratory from 3-centimeter undisturbed core samples within the -30 to -130 cm matric potential range. At higher potentials, core samples systematically exhibited significantly higher water contents than the in situ profiles due probably to air entrapment in the latter. Soil matric potential did not decrease beyond -130 cm within the 0 to 90 cm depth after 42 days of free internal drainage, but the corresponding residual water contents were quite low (0.03 cm^3 cm^{-3} at 15 cm depth and h = -130 cm). Drainage did not cease completely at the end of the 42 days, despite the sandy texture of the soil in the experimental site.

Seasonal water budgets measured during two field experiments involving corn, sorghum and peanut in 1986 and 1987 showed that substantial amounts of water were lost by deep drainage below the root zone in all water treatments. Seasonal drainage was highest in peanut followed by sorghum and then corn, and increased with increasing irrigation amount. The water losses occurred whenever an unanticipated heavy rainfall replenished the depleted root zone in excess of the water holding capacity of the soil.

Actual ET rates for each crop increased steadily with increasing canopy ground cover from planting to mid-season then decreased during late grain filling stages, mainly because of leaf senescence. At mid-season, actual ET rates of corn and sorghum in the well-irrigated treatment exceeded potential ET based on Penman formula, probably because of the roughness of their respective canopies and relatively small sizes of the plots which may have caused significant energy transfer by advection. Actual ET rates of peanut seldom exceeded potential ET. Evapotranspiration rates of Pioneer Brand 3165 corn was very similar to that of Northrup King Savanna 5 sorghum up until the mid-season of the latter crop; ET rates of sorghum

dropped significantly during the grain filling growth phase while maize continued to use water at its peak rate for a longer time period. Southern Runner peanut seemed to have lower water uptake rates than either one of the two grasses as indicated by higher soil water contents and water potentials in peanut subplots throughout the growing season in all treatments. The extensive and supposedly deep root system of peanut may not totally explain the observed discrepancies since sorghum also exhibited a similar and even more extensive rooting habit. Further investigations in that area will be needed. The optimum water management in 1987 based on corn water requirements resulted in substantial losses of water by deep drainage during the late growth phases of sorghum and throughout the growing cycle of peanut. This explains the better irrigation production functions (higher coefficients of determination) obtained with corn as compared to those obtained with the two other crops. Seasonal ET of all the three crops were lower than potential ET based on Turc, Penman or pan class A methods. Corn also had a higher irrigation-use efficiency (82%) than sorghum (45%) and peanut (34%), as well as a higher transpirational water-use efficiency (m = 192, 168 and 90 kg dry matter ha^{-1} day^{-1} for corn, sorghum and peanut, respectively).

The yield versus ET regression functions were all significant in 1987, showing that yields of all the three crops would respond linearly to water input if water management strategy is adjusted to satisfy the specific water requirements of the individual crops. Thus, the soil water potential thresholds at which corn, sorghum and peanut should be irrigated to avoid any deleterious soil water deficit that could reduce grain yield must be crop-dependent. For Gainesville conditions, it appears that maintaining soil matric potential at - 200 millibars or higher in the root zone would result in optimum yield for corn, even though such high matric potentials may contribute to significant water loss by deep drainage due to unexpected rainfalls. The same threshold value can be applicable to grain sorghum until the end of the

flowering phase after which it should be decreased to -500 millibars up until harvest. Irrigation should be applied to peanut whenever the matric potential in the root zone drops to -500 millibars throughout the growth cycle. The amount of water applied at each irrigation event should be adjusted to the growth stage of the crop.

Sole crop yields in the well-irrigated treatments were near their regional optima for all the three crops grown in both seasons. The extended growing season resulted in very high yield of Southern Runner peanut in 1987, suggesting that its optimum harvest time should be around 180-190 days for an early planting in Gainesville.

Despite these high yield levels, sorghum-peanut intercrop produced between 15 and 36% more than pure stands of these crops in 1987, based on LER concept. But the yield advantages practically disappeared or become negligible when the analysis took into account both the land area and the water resources used (LWUER). Yield advantages of intercropping increased with increasing irrigation, suggesting that intercrop system may have been under more water stress than the corresponding sole crops. The 1987 yield advantages came about through a combination of temporal and spatial complementarities of the two component crops. Such complementarities were greatest when the component crops were more or less equally competitive so that each one could exert a reasonable pressure on the available resources. The use of conjugate water production functions and land water-use equivalency ratio concepts may be helpful in comparing biological efficiencies of cropping systems. Based on these concepts, sorghum-peanut intercropping was not significantly more water-use efficient than sole cropping.

This study demonstrates that productivity of the best-performing sole crop systems can still be improved by coupling water management with intercropping. But intercrop system did not provide a better stability of yield than sole crops.

APPENDIX A
FIELD-DETERMINED HYDRODYNAMIC CHARACTERISTICS
OF SOIL IN PLOTS 9 AND 16, UNIT 2, IRRIGATION
RESEARCH AND EDUCATION PARK, GAINESVILLE.

PLOT 09 PROFILE 1

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm					
	15			30		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.035	0.115005	-25.000	.	0.148416	-9.670	.
0.183	0.096550	-31.880	.	0.128241	-21.855	23.083660
0.283	0.073673	-41.900	.	0.102792	-37.255	4.028162
0.923	0.060044	-53.580	.	0.086088	-49.180	1.295225
1.096	0.049816	-63.360	.	0.073339	-59.155	0.527941
1.298	0.047859	-65.820	.	0.070797	-61.665	0.413962
2.094	0.044616	-70.495	.	0.066496	-66.435	0.258363
2.297	0.041916	-74.620	.	0.062881	-70.640	0.172542
3.117	0.040334	-77.490	.	0.060698	-73.570	0.129072
3.304	0.038937	-80.115	.	0.058757	-76.250	0.099574
4.317	0.037836	-82.470	.	0.057190	-78.650	0.078454
5.290	0.036333	-85.865	.	0.055027	-82.120	0.055936
6.312	0.035234	-88.610	.	0.053415	-84.920	0.042561
7.265	0.034383	-90.905	.	0.052149	-87.255	0.033968
8.310	0.033692	-92.890	.	0.051109	-89.280	0.027977
10.310	0.032872	-95.415	.	0.049862	-91.860	0.021885
12.300	0.032003	-98.245	.	0.048537	-94.750	0.016760
14.310	0.031317	-100.615	.	0.047495	-97.165	0.013515
18.280	0.030524	-103.475	.	0.046318	-100.085	0.010546
21.310	0.029739	-106.350	.	0.045190	-103.020	0.008421
24.290	0.029173	-108.405	.	0.044431	-105.115	0.007302
29.300	0.028509	-110.705	.	0.043622	-107.460	0.006380
38.290	0.027443	-113.990	.	0.042530	-110.815	0.005541
42.260	0.026489	-116.635	.	0.041687	-113.515	0.005195

PLOT 9 PROFILE 1 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
0.035	0.159895	-22.000	.	0.170097	-20.280	.
0.183	0.145075	-33.425	6.324513	0.153023	-29.970	18.755150
0.283	0.124552	-37.105	4.472196	0.130516	-42.215	4.548557
0.923	0.107226	-39.305	4.260217	0.112966	-51.695	1.101832
1.096	0.094321	-51.715	1.201486	0.099435	-59.625	0.549609
1.298	0.091856	-56.560	0.724319	0.096709	-61.620	0.495712
2.094	0.087724	-65.015	0.333638	0.092094	-65.415	0.409008
2.297	0.084261	-72.115	0.185951	0.088216	-68.760	0.366539
3.117	0.082178	-76.120	0.131785	0.085878	-71.090	0.323708
3.304	0.080327	-79.595	0.098184	0.083802	-73.220	0.291839
4.317	0.078828	-82.055	0.077712	0.082130	-75.130	0.247954
5.290	0.076757	-85.190	0.057151	0.079828	-77.890	0.188148
6.312	0.075206	-87.165	0.046035	0.078117	-80.115	0.140360
7.265	0.073981	-88.475	0.039366	0.076777	-81.975	0.105743
8.310	0.072971	-89.360	0.035109	0.075679	-83.585	0.080861
10.310	0.071753	-90.185	0.031339	0.074370	-85.635	0.056346
12.300	0.070449	-90.865	0.028975	0.072982	-87.930	0.037649
14.310	0.069415	-91.255	0.028662	0.071896	-89.850	0.026999
18.280	0.068236	-91.665	0.030874	0.070675	-92.175	0.018391
21.310	0.067097	-92.170	0.038757	0.069511	-94.505	0.012940
24.290	0.066321	-92.755	0.052194	0.068731	-96.170	0.010354
29.300	0.065488	-93.905	0.081428	0.067905	-98.040	0.008399
38.290	0.064349	-97.065	0.078046	0.066796	-100.705	0.006963
42.260	0.063461	-100.815	0.037959	0.065943	-102.850	0.006632

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.035	0.164529	.	.	0.155100	-21.650	.
0.183	0.148307	.	.	0.145767	-31.235	19.574310
0.283	0.127872	.	.	0.133291	-43.345	8.334829
0.923	0.112600	.	.	0.112347	-52.725	3.124181
1.096	0.100015	.	.	0.093137	-60.575	1.307847
1.298	0.097012	.	.	0.090480	-62.550	1.039748
2.094	0.091581	.	.	0.086167	-66.310	0.669068

PLOT 9 PROFILE 1 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	75 PHEAD cm	75 K cm/day	90 THETA cm3/cm3	90 PHEAD cm	90 K cm/day
2.297	0.086905	.	.	0.082562	-69.625	0.460155
3.117	0.083942	.	.	0.080320	-71.940	0.350614
3.304	0.081298	.	.	0.078308	-74.060	0.274701
4.317	0.079182	.	.	0.076618	-75.970	0.218648
5.290	0.076327	.	.	0.074247	-78.740	0.157178
6.312	0.074325	.	.	0.072432	-80.990	0.119494
7.265	0.072875	.	.	0.070980	-82.890	0.094522
8.310	0.071808	.	.	0.069773	-84.555	0.076759
10.310	0.070748	.	.	0.068313	-86.710	0.058423
12.300	0.069857	.	.	0.066752	-89.180	0.042787
14.310	0.069398	.	.	0.065521	-91.315	0.032865
18.280	0.069171	.	.	0.064134	-94.050	0.024014
21.310	0.069090	.	.	0.062813	-96.960	0.018073
24.290	0.069039	.	.	0.061933	-99.225	0.015342
29.300	0.068713	.	.	0.061007	-102.045	0.013601
38.290	0.066948	.	.	0.059782	-106.790	0.013148
42.260	0.064324	.	.	0.058852	-111.140	0.014008

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm			
0.035	.	.	.	.
0.183	0.142146	0.138800	.	.
0.283	0.134219	0.134191	0.135700	.
0.923	0.111026	0.117294	0.128246	.
1.096	0.094103	0.103265	0.121234	.
1.298	0.090920	0.099829	0.121137	0.178765
2.094	0.085582	0.093460	0.116306	0.173400
2.297	0.081108	0.087909	0.110947	0.166488
3.117	0.078411	0.084215	0.106182	0.159371
3.304	0.076012	0.080877	0.101763	0.152689
4.317	0.074066	0.078038	0.097751	0.146369
5.290	0.071372	0.074059	0.092017	0.137150
6.312	0.069350	0.071035	0.087523	0.129646

PLOT 9 PROFILE 1 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm			
7.265	0.067751	0.068652	0.083899	0.123385
8.310	0.066428	0.066710	0.080881	0.117985
10.310	0.064831	0.064442	0.077256	0.111192
12.300	0.063118	0.062119	0.073432	0.103704
14.310	0.061757	0.060404	0.070491	0.097610
18.280	0.060199	0.058658	0.067326	0.090614
21.310	0.058691	0.057128	0.064434	0.083961
24.290	0.057663	0.056211	0.062617	0.079664
29.300	0.056555	0.055289	0.060790	0.075535
38.290	0.055037	0.053888	0.058346	0.071366
42.260	0.053852	0.052564	0.056368	0.069304

PLOT 09 PROFILE 2

TIME AFTER INITIATION OF DRAIN-AGE (DAYS)	SOIL DEPTH, cm 15 THETA cm3/cm3	15 PHEAD cm	15 K cm/day	30 THETA cm3/cm3	30 PHEAD cm	30 K cm/day
0.040	0.113477	-20.420	.	0.142269	-24.290	.
0.188	0.094036	-30.065	.	0.123465	-33.820	6.251873
0.287	0.070816	-42.350	.	0.100077	-45.955	1.944858
0.928	0.059274	-52.305	.	0.085460	-55.785	0.632888
1.103	0.050642	-60.695	.	0.074261	-64.075	0.264068
1.303	0.048988	-62.810	.	0.072036	-66.165	0.209248
2.099	0.046220	-66.820	.	0.068276	-70.125	0.133572
2.303	0.043891	-70.370	.	0.065101	-73.630	0.091207
3.123	0.042493	-72.845	.	0.063180	-76.075	0.069320
3.308	0.041255	-75.100	.	0.061475	-78.305	0.054414
4.322	0.040255	-77.125	.	0.060094	-80.310	0.043500
5.294	0.038875	-80.055	.	0.058184	-83.210	0.031703
6.316	0.037847	-82.420	.	0.056759	-85.545	0.024572
7.269	0.037038	-84.395	.	0.055636	-87.495	0.019898
8.314	0.036373	-86.110	.	0.054712	-89.185	0.016593
10.310	0.035576	-88.290	.	0.053605	-91.335	0.013149
12.310	0.034726	-90.735	.	0.052423	-93.755	0.010157
14.320	0.034055	-92.785	.	0.051490	-95.780	0.008208
18.290	0.033297	-95.255	.	0.050436	-98.215	0.006338

PLOT 9 PROFILE 2 -- continued

TIME AFTER INITIATION OF DRAIN-AGE (DAYS)	SOIL DEPTH, cm 15			30		
	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
21.310	0.032570	-97.730	.	0.049425	-100.665	0.004914
24.300	0.032078	-99.500	.	0.048742	-102.415	0.004101
29.310	0.031552	-101.490	.	0.048011	-104.375	0.003348
38.300	0.030839	-104.325	.	0.047023	-107.180	0.002511
42.270	0.030287	-106.605	.	0.046258	-109.435	0.002000

TIME AFTER INITIATION OF DRAIN-AGE (DAYS)	SOIL DEPTH, cm 45			60		
	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.040	0.156877	-25.930	.	0.158212	-26.687	.
0.188	0.138172	-36.250	9.998720	0.142416	-34.267	17.417150
0.287	0.115782	-49.370	2.985399	0.122396	-43.920	7.638862
0.928	0.103785	-59.790	0.954229	0.108487	-51.739	3.518575
1.103	0.094429	-68.505	0.396070	0.097626	-58.332	2.185514
1.303	0.092413	-70.640	0.314537	0.095370	-59.993	1.937191
2.099	0.088832	-74.572	0.202909	0.091477	-63.140	1.535301
2.303	0.085742	-78.007	0.140247	0.088160	-65.925	1.303493
3.123	0.083744	-80.279	0.108180	0.086096	-67.863	1.131122
3.308	0.081949	-82.323	0.086203	0.084256	-69.628	1.004895
4.322	0.080426	-84.043	0.070304	0.082736	-71.206	0.863979
5.294	0.078279	-86.436	0.052998	0.080618	-73.483	0.673071
6.316	0.076626	-88.217	0.042542	0.079018	-75.309	0.514505
7.269	0.075297	-89.588	0.035705	0.077749	-76.824	0.391488
8.314	0.074189	-90.666	0.030895	0.076703	-78.126	0.297190
10.310	0.072848	-91.846	0.026023	0.075454	-79.757	0.199094
12.310	0.071414	-92.950	0.021929	0.074136	-81.553	0.123614
14.320	0.070290	-93.619	0.019503	0.073124	-83.012	0.081031
18.290	0.069058	-93.986	0.017770	0.072059	-84.672	0.047170
21.310	0.067920	-93.978	0.017582	0.071126	-86.238	0.027487
24.300	0.067206	-93.585	0.019459	0.070606	-87.239	0.018377
29.310	0.066521	-92.662	0.029090	0.070225	-88.182	0.011428
38.300	0.065778	-90.358	-0.03746	0.070162	-89.071	0.005447
42.270	0.065331	-87.857	-0.00781	0.070462	-89.447	0.002720

PLOT 9 PROFILE 2 -- continued

TIME AFTER INITIATION OF DRAIN-AGE (DAYS)	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.040	0.163385	.	.	0.143600	-29.903	.
0.188	0.148848	.	.	0.138818	-32.462	21.437230
0.287	0.128837	.	.	0.126286	-36.885	10.890280
0.928	0.110683	.	.	0.106581	-44.797	3.551866
1.103	0.096513	.	.	0.093280	-51.798	1.502388
1.303	0.093673	.	.	0.090681	-53.674	1.190273
2.099	0.088922	.	.	0.086042	-57.283	0.758323
2.303	0.084933	.	.	0.082032	-60.492	0.516419
3.123	0.082572	.	.	0.079438	-62.757	0.390775
3.308	0.080489	.	.	0.077112	-64.824	0.305019
4.322	0.078842	.	.	0.075174	-66.689	0.242421
5.294	0.076592	.	.	0.072485	-69.392	0.174411
6.316	0.074955	.	.	0.070490	-71.579	0.133252
7.269	0.073695	.	.	0.068951	-73.410	0.106132
8.314	0.072684	.	.	0.067729	-74.999	0.086821
10.310	0.071512	.	.	0.066359	-77.022	0.066827
12.310	0.070304	.	.	0.065015	-79.297	0.049434
14.320	0.069400	.	.	0.064090	-81.203	0.038024
18.290	0.068462	.	.	0.063260	-83.502	0.027110
21.310	0.067637	.	.	0.062617	-85.811	0.018849
24.300	0.067160	.	.	0.062300	-87.462	0.014157
29.310	0.066758	.	.	0.062015	-89.316	0.009856
38.300	0.066468	.	.	0.061470	-91.962	0.005226
42.270	0.066427	.	.	0.060806	-94.093	0.002596

TIME AFTER INITIATION OF DRAIN-AGE (DAYS)	SOIL DEPTH, cm 105	120	135
	THETA, cm		
0.188	0.130098	.	.
0.287	0.125077	0.127945	0.145981
0.928	0.106933	0.115440	0.136329
1.103	0.092175	0.101185	0.125257
1.303	0.089049	0.097814	0.122467
2.099	0.083748	0.091954	0.117185

PLOT 9 PROFILE 2 -- continued

TIME AFTER INITIATION OF DRAIN-AGE (DAYS)	SOIL DEPTH, cm 105	120	135
	THETA, cm		
2.303	0.079273	0.086962	0.112513
3.123	0.076588	0.083902	0.109263
3.308	0.074214	0.081187	0.106305
4.322	0.072321	0.078997	0.103664
5.294	0.069391	0.075982	0.099858
6.316	0.067000	0.073757	0.096816
7.269	0.065859	0.072024	0.094299
8.314	0.065152	0.070616	0.092145
10.310	0.063750	0.068956	0.089467
12.310	0.062282	0.067213	0.086542
14.320	0.061151	0.065868	0.084203
18.290	0.059915	0.064391	0.081620
21.310	0.058758	0.063006	0.079268
24.300	0.058001	0.062098	0.077875
29.310	0.057217	0.061155	0.076746
38.300	0.056197	0.059927	0.076234
42.270	0.055432	0.059003	0.076643

PLOT 09 PROFILE 3

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm 15			30		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.043	0.108715	-25.470	.	0.141015	-26.420	.
0.193	0.090342	-34.460	.	0.120857	-34.965	7.282521
0.292	0.067979	-45.915	.	0.095902	-45.865	2.548647
0.935	0.055603	-55.245	.	0.080763	-54.845	0.850934
1.109	0.046291	-63.100	.	0.069262	-62.445	0.354397
1.307	0.044540	-65.035	.	0.067065	-64.355	0.279329
2.103	0.041634	-68.685	.	0.063401	-68.005	0.174917
2.309	0.039196	-71.915	.	0.060322	-71.250	0.116575
3.128	0.037774	-74.115	.	0.058514	-73.520	0.086689
3.313	0.036525	-76.100	.	0.056924	-75.590	0.066434
4.326	0.035543	-77.840	.	0.055664	-77.455	0.051892
5.298	0.034203	-80.330	.	0.053938	-80.170	0.036344
6.320	0.033229	-82.295	.	0.052670	-82.380	0.027145

PLOT 9 PROFILE 3 -- continued

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm					
	15			30		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
7.273	0.032479	-83.910	.	0.051681	-84.240	0.021237
8.319	0.031875	-85.285	.	0.050871	-85.875	0.017150
10.320	0.031169	-87.015	.	0.049896	-87.995	0.013028
12.310	0.030434	-88.945	.	0.048846	-90.420	0.009621
14.320	0.029872	-90.560	.	0.047994	-92.515	0.007500
18.290	0.029259	-92.595	.	0.046960	-95.200	0.005596
21.320	0.028686	-94.760	.	0.045888	-98.055	0.004274
24.300	0.028313	-96.475	.	0.045062	-100.275	0.003580
29.310	0.027928	-98.720	.	0.044020	-103.045	0.003031
38.300	0.027429	-102.870	.	0.042189	-107.705	0.002555
42.270	0.027054	-106.960	.	0.040448	-111.980	0.002376

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm					
	45			60		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.043	0.159314	-35.310	.	0.161424	-24.610	.
0.193	0.140850	-42.675	7.523018	0.145505	-32.515	45.954850
0.292	0.117917	-52.075	2.789314	0.124525	-42.600	14.628130
0.935	0.103415	-59.820	0.978906	0.107836	-50.905	4.459107
1.109	0.092199	-66.365	0.428665	0.094857	-57.925	1.735439
1.307	0.089940	-68.005	0.343376	0.092291	-59.685	1.348836
2.103	0.086055	-71.145	0.222741	0.087973	-63.055	0.826473
2.309	0.082745	-73.940	0.153523	0.084332	-66.050	0.542045
3.128	0.080712	-75.885	0.117547	0.082179	-68.140	0.400387
3.313	0.078907	-77.655	0.092757	0.080285	-70.040	0.305742
4.326	0.077426	-79.250	0.074661	0.078785	-71.745	0.239196
5.298	0.075365	-81.550	0.054916	0.076733	-74.220	0.168193
6.320	0.073810	-83.410	0.042953	0.075235	-76.215	0.126776
7.273	0.072574	-84.965	0.035072	0.074077	-77.880	0.100285
8.319	0.071550	-86.310	0.029551	0.073142	-79.330	0.081911
10.320	0.070309	-88.030	0.023857	0.072046	-81.175	0.063421
12.310	0.068977	-89.955	0.019023	0.070904	-83.235	0.048004
14.320	0.067916	-91.560	0.015980	0.070028	-84.955	0.038289

PLOT 09 PROFILE 3 -- continued

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm 45			60		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
18.290	0.066701	-93.500	0.013288	0.069069	-87.040	0.029372
21.320	0.065525	-95.455	0.011509	0.068172	-89.135	0.022991
24.300	0.064722	-96.850	0.010769	0.067587	-90.630	0.019550
29.310	0.063856	-98.410	0.010628	0.066983	-92.305	0.016661
38.300	0.062671	-100.640	0.012278	0.066198	-94.700	0.013857
42.270	0.061745	-102.435	0.017023	0.065609	-96.630	0.012515

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm 75			90		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.043	0.169301	.	.	0.160952	-21.792	.
0.193	0.149880	.	.	0.145595	-28.043	25.665640
0.292	0.125620	.	.	0.124757	-36.030	10.821750
0.935	0.108955	.	.	0.106427	-42.726	4.030403
1.109	0.095693	.	.	0.092071	-48.430	1.833128
1.307	0.092949	.	.	0.089202	-49.898	1.475366
2.103	0.088268	.	.	0.084364	-52.763	0.961759
2.309	0.084300	.	.	0.080280	-55.338	0.664128
3.128	0.081922	.	.	0.077860	-57.204	0.506306
3.313	0.079824	.	.	0.075729	-58.917	0.397201
4.326	0.078150	.	.	0.074039	-60.519	0.316703
5.298	0.075853	.	.	0.071726	-62.894	0.228500
6.320	0.074168	.	.	0.070036	-64.897	0.174645
7.273	0.072861	.	.	0.068730	-66.637	0.139049
8.319	0.071804	.	.	0.067674	-68.208	0.113896
10.320	0.070559	.	.	0.066436	-70.318	0.087802
12.310	0.069260	.	.	0.065145	-72.806	0.065484
14.320	0.068261	.	.	0.064154	-75.030	0.051110
18.290	0.067165	.	.	0.063069	-77.966	0.037648
21.320	0.066139	.	.	0.062055	-81.131	0.027864
24.300	0.065468	.	.	0.061393	-83.611	0.022492
29.310	0.064774	.	.	0.060709	-86.661	0.017799
38.300	0.063870	.	.	0.059820	-91.579	0.012981
42.270	0.063191	.	.	0.059152	-95.905	0.010419

PLOT 9 PROFILE 3 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm			
0.193	0.130788	0.138960	0.140178	.
0.292	0.125780	0.133423	0.135966	.
0.935	0.105408	0.111153	0.120026	0.131514
1.109	0.088316	0.092496	0.106604	0.132691
1.307	0.085054	0.088843	0.103286	0.133541
2.103	0.079709	0.082780	0.097034	0.128527
2.309	0.075249	0.077693	0.091509	0.122620
3.128	0.072685	0.074713	0.087755	0.117207
3.313	0.070439	0.072092	0.084363	0.112202
4.326	0.068686	0.070015	0.081407	0.107611
5.298	0.066300	0.067170	0.077204	0.101000
6.320	0.064569	0.065082	0.073930	0.095760
7.273	0.063234	0.063460	0.071287	0.091486
8.319	0.062156	0.062142	0.069083	0.087888
10.320	0.060883	0.060582	0.066429	0.083508
12.310	0.059541	0.058940	0.063635	0.078840
14.320	0.058487	0.057666	0.061501	0.075213
18.290	0.057277	0.056246	0.059273	0.071305
21.320	0.056084	0.054899	0.057335	0.067791
24.300	0.055231	0.054004	0.056262	0.065705
29.310	0.054234	0.053062	0.055444	0.063896
38.300	0.052647	0.051807	0.055062	0.062389
42.270	0.051231	0.050846	0.055273	0.061885

PLOT 9 PROFILE 4

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 15			30		
	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.050	0.116300	-27.020	.	0.147023	-24.000	.
0.198	0.099330	-35.315	.	0.126752	-33.915	7.956882
0.297	0.073613	-46.060	.	0.101205	-46.190	4.734347
0.942	0.056588	-55.525	.	0.084267	-55.260	0.864008
1.115	0.047435	-63.575	.	0.071294	-62.950	0.356064
1.313	0.045749	-65.615	.	0.068798	-64.880	0.288133

PLOT 9 PROFILE 4 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 15 THETA cm3/cm3	PHEAD cm	K cm/day	30 THETA cm3/cm3	PHEAD cm	K cm/day
2.109	0.042815	-69.555	.	0.064609	-68.580	0.188935
2.314	0.040317	-73.075	.	0.061086	-71.870	0.130641
3.135	0.038809	-75.575	.	0.059013	-74.175	0.099849
3.317	0.037481	-77.850	.	0.057192	-76.270	0.078441
4.332	0.036426	-79.930	.	0.055756	-78.150	0.062880
5.303	0.034980	-82.975	.	0.053790	-80.875	0.045849
6.324	0.033928	-85.475	.	0.052360	-83.070	0.035605
7.278	0.033115	-87.600	.	0.051256	-84.910	0.028891
8.323	0.032460	-89.475	.	0.050365	-86.510	0.024116
10.330	0.031693	-91.925	.	0.049320	-88.545	0.019261
12.320	0.030897	-94.735	.	0.048233	-90.820	0.015095
14.330	0.030289	-97.150	.	0.047402	-92.720	0.012427
18.300	0.029626	-100.200	.	0.046493	-95.020	0.009952
21.320	0.029009	-103.375	.	0.045645	-97.330	0.008120
24.310	0.028607	-105.755	.	0.045091	-98.980	0.007168
29.320	0.028192	-108.570	.	0.044519	-100.830	0.006393
38.310	0.027655	-112.875	.	0.043777	-103.475	0.005890
42.280	0.027254	-116.525	.	0.043220	-105.600	0.006168

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
0.050	0.159553	-23.230	.	0.168855	-25.150	.
0.198	0.141806	-31.635	13.051130	0.151223	-34.130	12.563360
0.297	0.119459	-42.515	8.306943	0.128239	-45.400	6.524576
0.942	0.104479	-52.035	1.734231	0.110571	-53.670	1.703535
1.115	0.092895	-60.110	0.689702	0.096838	-60.475	0.767523
1.313	0.090594	-62.140	0.546956	0.094135	-62.085	0.630075
2.109	0.086656	-66.030	0.345519	0.089570	-65.110	0.428341
2.314	0.083314	-69.485	0.231605	0.085723	-67.785	0.307977
3.135	0.081286	-71.905	0.173012	0.083446	-69.615	0.243060
3.317	0.079493	-74.105	0.133258	0.081444	-71.270	0.197355
4.332	0.078040	-76.080	0.104708	0.079859	-72.740	0.163242
5.303	0.076025	-78.945	0.074036	0.077688	-74.860	0.124903
6.324	0.074528	-81.255	0.055882	0.076105	-76.555	0.101007

PLOT 9 PROFILE 4 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
7.278	0.073339	-83.185	0.044202	0.074881	-77.960	0.084905
8.323	0.072364	-84.860	0.036022	0.073892	-79.175	0.073168
10.330	0.071194	-87.000	0.027716	0.072732	-80.720	0.060752
12.320	0.069948	-89.395	0.020680	0.071523	-82.440	0.049730
14.330	0.068968	-91.395	0.016215	0.070598	-83.870	0.042380
18.300	0.067860	-93.810	0.012060	0.069585	-85.590	0.035166
21.320	0.066797	-96.235	0.008982	0.068639	-87.310	0.029586
24.310	0.066079	-97.970	0.007285	0.068022	-88.535	0.026422
29.320	0.065312	-99.915	0.005744	0.067383	-89.910	0.023448
38.310	0.064276	-102.690	0.004098	0.066554	-91.865	0.020300
42.280	0.063474	-104.925	0.003135	0.065932	-93.430	0.018724

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.050	0.165900	.	.	0.153278	-25.217	.
0.198	0.149188	.	.	0.146198	-30.543	23.335250
0.297	0.126943	.	.	0.131322	-37.451	15.575150
0.942	0.108421	.	.	0.107655	-43.620	4.735163
1.115	0.093922	.	.	0.090124	-48.895	2.141364
1.313	0.091038	.	.	0.086984	-50.257	1.726072
2.109	0.086155	.	.	0.081832	-52.938	1.119523
2.314	0.082035	.	.	0.077540	-55.348	0.767723
3.135	0.079589	.	.	0.075071	-57.109	0.579600
3.317	0.077438	.	.	0.072911	-58.725	0.450381
4.332	0.075733	.	.	0.071229	-60.245	0.355224
5.303	0.073396	.	.	0.068939	-62.508	0.251598
6.324	0.071691	.	.	0.067288	-64.422	0.189149
7.278	0.070371	.	.	0.066020	-66.095	0.148333
8.323	0.069305	.	.	0.065002	-67.613	0.119586
10.330	0.068053	.	.	0.063815	-69.665	0.090212
12.320	0.066748	.	.	0.062584	-72.096	0.065471
14.330	0.065749	.	.	0.061647	-74.278	0.049770
18.300	0.064655	.	.	0.060627	-77.181	0.035283
21.320	0.063632	.	.	0.059678	-80.323	0.024856

PLOT 9 PROFILE 4 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
24.310	0.062964	.	.	0.059061	-82.803	0.019212
29.320	0.062273	.	.	0.058425	-85.876	0.014254
38.310	0.061376	.	.	0.057602	-90.859	0.009183
42.280	0.060703	.	.	0.056986	-95.260	0.006445

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105 THETA cm3/cm3	PHEAD cm	K cm/day
0.198	0.136234	.	.
0.297	0.133013	.	.
0.942	0.112615	.	.
1.115	0.093398	.	.
1.313	0.089528	.	.
2.109	0.083133	.	.
2.314	0.077794	.	.
3.135	0.074713	.	.
3.317	0.072017	.	.
4.332	0.069917	.	.
5.303	0.067056	.	.
6.324	0.064993	.	.
7.278	0.063408	.	.
8.323	0.062136	.	.
10.330	0.060652	.	.
12.320	0.059114	.	.
14.330	0.057943	.	.
18.300	0.056669	.	.
21.320	0.055482	.	.
24.310	0.054711	.	.
29.320	0.053916	.	.
38.310	0.052887	.	.
42.280	0.052117	.	.

PLOT 9 PROFILE 5

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 15 THETA cm3/cm3	PHEAD cm	K cm/day	30 THETA cm3/cm3	PHEAD cm	K cm/day
0.051	0.105329	-28.680	.	0.143904	-22.420	.
0.203	0.088336	-36.045	.	0.122859	-35.990	7.133739
0.300	0.068045	-45.505	.	0.097662	-52.075	1.510366
0.946	0.057404	-53.810	.	0.084105	-60.255	0.510573
1.119	0.049207	-60.945	.	0.073589	-66.645	0.230648
1.317	0.047568	-62.770	.	0.071448	-68.065	0.189561
2.114	0.044704	-66.320	.	0.067674	-70.865	0.129714
2.319	0.042250	-69.495	.	0.064429	-73.410	0.094350
3.139	0.040710	-71.765	.	0.062370	-75.390	0.074472
3.322	0.039336	-73.845	.	0.060529	-77.240	0.060556
4.335	0.038187	-75.765	.	0.058977	-79.120	0.049553
5.307	0.036568	-78.590	.	0.056783	-82.035	0.037078
6.327	0.035325	-80.935	.	0.055088	-84.670	0.029076
7.282	0.034322	-82.950	.	0.053714	-87.075	0.023572
8.326	0.033479	-84.745	.	0.052554	-89.330	0.019537
10.330	0.032441	-87.115	.	0.051119	-92.445	0.015314
12.320	0.031310	-89.870	.	0.049550	-96.135	0.011641
14.330	0.030396	-92.285	.	0.048275	-99.355	0.009276
18.300	0.029327	-95.400	.	0.046777	-103.195	0.007149
21.320	0.028277	-98.690	.	0.045302	-106.760	0.005645
24.310	0.027547	-101.210	.	0.044272	-108.755	0.004913
29.320	0.026747	-104.250	.	0.043139	-109.810	0.004503
38.310	0.025633	-109.025	.	0.041553	-107.530	0.005314
42.290	0.024750	-113.160	.	0.040295	-102.565	0.013327

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
0.050	0.159499	-35.910	.	0.160007	-28.410	.
0.203	0.140715	-42.445	7.717100	0.144161	-34.955	28.872420
0.300	0.118082	-50.830	3.717832	0.123953	-43.350	9.332947
0.946	0.105219	-58.185	1.342951	0.109378	-50.635	3.229720
1.119	0.095106	-64.505	0.594817	0.097950	-56.865	1.447953
1.317	0.092985	-66.115	0.473484	0.095614	-58.435	1.177114
2.114	0.089205	-69.250	0.305456	0.091511	-61.450	0.792816

PLOT 9 PROFILE 5 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
2.319	0.085943	-72.050	0.211666	0.087991	-64.130	0.569708
3.139	0.083857	-74.050	0.164624	0.085775	-66.000	0.452151
3.322	0.081992	-75.885	0.132547	0.083799	-67.700	0.370746
4.335	0.080421	-77.570	0.109875	0.082149	-69.230	0.309840
5.307	0.078209	-80.045	0.085448	0.079832	-71.450	0.241962
6.327	0.076514	-82.100	0.071180	0.078068	-73.240	0.200379
7.282	0.075156	-83.860	0.062064	0.076660	-74.735	0.172601
8.326	0.074025	-85.425	0.055855	0.075495	-76.035	0.152610
10.330	0.072658	-87.490	0.050007	0.074101	-77.695	0.132390
12.320	0.071203	-89.880	0.045426	0.072638	-79.550	0.115438
14.330	0.070066	-91.970	0.042872	0.071530	-81.100	0.105882
18.300	0.068816	-94.650	0.039826	0.070400	-82.975	0.101026
21.320	0.067660	-97.470	0.035470	0.069460	-84.855	0.106928
24.310	0.066931	-99.630	0.028953	0.069009	-86.200	0.131161
29.320	0.066227	-102.225	0.018836	0.068819	-87.710	0.326640
38.310	0.065448	-106.275	0.007617	0.069324	-89.865	-0.071710
42.290	0.064966	-109.765	0.003726	0.070302	-91.595	-0.019810

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.051	0.163839	.	.	0.160948	-31.301	.
0.203	0.147219	.	.	0.149304	-33.063	21.824540
0.300	0.125641	.	.	0.131074	-36.215	10.372020
0.946	0.108790	.	.	0.109672	-43.081	3.658874
1.119	0.095520	.	.	0.093255	-49.488	1.582527
1.317	0.092891	.	.	0.090217	-51.348	1.254173
2.114	0.088438	.	.	0.085198	-55.094	0.792431
2.319	0.084682	.	.	0.081607	-58.480	0.534931
3.139	0.082458	.	.	0.078590	-60.949	0.401959
3.322	0.080501	.	.	0.076473	-63.210	0.312461
4.335	0.078950	.	.	0.074821	-65.290	0.247298
5.307	0.076824	.	.	0.072571	-68.338	0.177278
6.327	0.075272	.	.	0.070946	-70.836	0.135417
7.282	0.074072	.	.	0.069697	-72.948	0.108026

PLOT 9 PROFILE 5 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
8.326	0.073102	.	.	0.068694	-74.796	0.088675
10.330	0.071964	.	.	0.067525	-77.172	0.068800
12.320	0.070778	.	.	0.066312	-79.853	0.051657
14.330	0.069869	.	.	0.065388	-82.111	0.040443
18.300	0.068874	.	.	0.064382	-84.861	0.029711
21.320	0.067944	.	.	0.063446	-87.638	0.021483
24.310	0.067337	.	.	0.062837	-89.634	0.016688
29.302	0.066709	.	.	0.062209	-91.885	0.012170
38.310	0.065894	.	.	0.061397	-95.114	0.006921
42.290	0.065282	.	.	0.060789	-97.724	0.003537

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm3/cm3			
0.051	0.146296	.	.	.
0.203	0.142252	0.138488	0.136468	.
0.300	0.131286	0.131170	0.129519	.
0.946	0.109393	0.110893	0.115916	.
1.119	0.092766	0.096188	0.108006	0.142741
1.317	0.089606	0.092803	0.105438	0.142619
2.114	0.084240	0.086754	0.099877	0.138472
2.319	0.079702	0.081550	0.094736	0.133271
3.139	0.076977	0.078314	0.090826	0.127761
3.322	0.074570	0.075444	0.087231	0.122557
4.335	0.072636	0.073111	0.083912	0.117441
5.307	0.069969	0.069883	0.079076	0.109858
6.327	0.068002	0.067489	0.075181	0.103586
7.282	0.066472	0.065617	0.071962	0.098300
8.326	0.065234	0.064092	0.069227	0.093719
10.330	0.063787	0.062288	0.065878	0.087951
12.320	0.062293	0.060393	0.062302	0.081611
14.330	0.061173	0.058931	0.059540	0.076501
18.300	0.060006	0.057318	0.056627	0.070754
21.320	0.058979	0.055804	0.054087	0.065437
24.310	0.058381	0.054809	0.052682	0.062182

PLOT 9 PROFILE 5 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm			
	105	120	135	150
	THETA, cm3/cm3			
29.320	0.057862	0.053776	0.051633	0.059362
38.310	0.057411	0.052429	0.051243	0.057451
42.290	0.057231	0.051414	0.051665	0.057493

PLOT 16 PROFILE 1

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm					
	15			30		
	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.003	0.143700	-6.000	.	0.184000	0	.
0.146	0.119499	-23.490	.	0.155904	-18.840	15.361930
0.252	0.089341	-44.320	.	0.120428	-41.155	4.529288
0.889	0.072331	-55.535	.	0.101339	-52.650	1.308029
1.056	0.060006	-64.500	.	0.088220	-61.765	0.574513
1.264	0.057457	-66.740	.	0.085368	-64.005	0.464751
2.055	0.053015	-71.035	.	0.080183	-68.240	0.308630
2.268	0.049257	-74.830	.	0.075715	-71.960	0.217711
3.080	0.046952	-77.520	.	0.072815	-74.535	0.168689
3.278	0.044912	-79.980	.	0.070218	-76.875	0.134032
4.284	0.043283	-82.235	.	0.068047	-78.975	0.107694
5.268	0.041090	-85.525	.	0.065054	-81.995	0.078166
6.291	0.039522	-88.260	.	0.062816	-84.440	0.059431
7.238	0.038371	-90.580	.	0.061103	-86.460	0.046808
8.282	0.037496	-92.635	.	0.059739	-88.210	0.037641
10.288	0.036558	-95.350	.	0.058183	-90.450	0.028002
12.282	0.035688	-98.505	.	0.056631	-92.955	0.019600
14.291	0.035133	-101.255	.	0.055529	-95.045	0.014321
18.250	0.034660	-104.765	.	0.054443	-97.565	0.010065
21.283	0.034275	-108.470	.	0.053485	-100.100	0.008201
24.267	0.034011	-111.300	.	0.052863	-101.915	0.009124
29.268	0.033580	-114.690	.	0.052098	-103.940	0.014608
38.265	0.032276	-119.995	.	0.050463	-106.840	0.056461
42.244	0.030584	-124.565	.	0.048603	-109.175	-0.401620

PLOT 16 PROFILE 1 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
0.003	0.188500	-5.300	.	0.176100	-11.000	.
0.146	0.166488	-22.030	13.090330	0.157160	-25.900	16.045180
0.252	0.138733	-41.985	5.145964	0.131482	-43.890	6.386131
0.889	0.121845	-52.650	1.594591	0.115233	-54.120	1.895196
1.056	0.109364	-61.110	0.749212	0.104760	-62.235	0.858807
1.264	0.106673	-63.190	0.615103	0.102837	-64.230	0.699921
2.055	0.101880	-67.120	0.418559	0.099472	-68.005	0.470403
2.268	0.097782	-70.575	0.301384	0.096605	-71.315	0.335826
3.080	0.095178	-72.965	0.235911	0.094751	-73.605	0.261724
3.278	0.092853	-75.140	0.188979	0.093083	-75.695	0.208972
4.284	0.090928	-77.090	0.152553	0.091642	-77.565	0.168477
5.268	0.088278	-79.890	0.111217	0.089601	-80.250	0.122836
6.291	0.086299	-82.160	0.084492	0.087988	-82.425	0.093638
7.238	0.084782	-84.035	0.066289	0.086678	-84.225	0.073874
8.282	0.083567	-85.655	0.053009	0.085564	-85.785	0.059477
10.288	0.082168	-87.730	0.038932	0.084172	-87.780	0.044261
12.282	0.080758	-90.060	0.026678	0.082651	-90.010	0.031073
14.291	0.079739	-92.005	0.018957	0.081428	-91.870	0.022689
18.250	0.078714	-94.340	0.012512	0.080042	-94.115	0.015447
21.283	0.077807	-96.690	0.008874	0.078735	-96.370	0.010998
24.267	0.077234	-98.375	0.008036	0.077901	-97.985	0.009493
29.268	0.076585	-100.255	0.008954	0.077117	-99.790	0.009491
38.265	0.075378	-102.945	0.013817	0.076371	-102.370	0.012611
42.244	0.074097	-105.115	0.020365	0.076047	-104.450	0.017378

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.003	0.169500	.	.	0.158800	-49.020	.
0.146	0.154037	.	.	0.148101	-44.490	16.398460
0.252	0.132354	.	.	0.132650	-42.360	11.152180
0.889	0.115226	.	.	0.114974	-51.380	3.436880
1.056	0.103099	.	.	0.100588	-58.985	1.524948
1.264	0.100664	.	.	0.097691	-61.020	1.228141

PLOT 16 PROFILE 1 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
2.055	0.096405	.	.	0.092805	-64.970	0.806133
2.268	0.092786	.	.	0.088724	-68.470	0.564015
3.080	0.090499	.	.	0.086272	-70.955	0.433785
3.278	0.088454	.	.	0.084102	-73.225	0.342849
4.284	0.086737	.	.	0.082341	-75.285	0.274336
5.268	0.084343	.	.	0.079919	-78.265	0.198467
6.291	0.082506	.	.	0.078096	-80.700	0.150968
7.238	0.081052	.	.	0.076670	-82.725	0.119379
8.282	0.079846	.	.	0.075495	-84.485	0.096719
10.288	0.078384	.	.	0.074069	-86.750	0.072915
12.282	0.076829	.	.	0.072541	-89.300	0.052381
14.291	0.075620	.	.	0.071332	-91.435	0.039256
18.250	0.074298	.	.	0.069954	-94.015	0.027568
21.283	0.073079	.	.	0.068622	-96.620	0.019704
24.267	0.072314	.	.	0.067713	-98.495	0.016175
29.268	0.071586	.	.	0.066736	-100.595	0.014169
38.265	0.070794	.	.	0.065400	-103.605	0.014660
42.244	0.070317	.	.	0.064356	-106.035	0.017355

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm3/cm3			
0.146	0.118544	0.134803	.	.
0.252	0.136749	0.139003	.	.
0.889	0.120187	0.131806	.	.
1.056	0.107116	0.127233	0.183237	0.245395
1.264	0.103959	0.126382	0.183443	0.244724
2.055	0.098077	0.121667	0.178698	0.245019
2.268	0.092950	0.116506	0.172158	0.245705
3.080	0.089503	0.111474	0.164973	0.242632
3.278	0.086388	0.106717	0.158149	0.238902
4.284	0.083690	0.102130	0.151444	0.232610
5.268	0.079889	0.095511	0.141597	0.221834
6.291	0.076931	0.090249	0.133444	0.211065
7.238	0.074581	0.086090	0.126677	0.201160

PLOT 16 PROFILE 1 -- continued

TIME AFTER INITIATION OF DRAINAGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm3/cm3			
8.282	0.072634	0.082721	0.120855	0.192038
10.288	0.070298	0.078869	0.113554	0.179959
12.282	0.067859	0.075092	0.105613	0.166377
14.291	0.066028	0.072543	0.099338	0.155343
18.250	0.064172	0.070379	0.092562	0.143175
21.283	0.062608	0.068851	0.086571	0.132214
24.267	0.061800	0.068263	0.083273	0.125882
29.268	0.061280	0.067895	0.081085	0.120912
38.265	0.061327	0.067018	0.081773	0.118475
42.240	0.061884	0.065626	0.085176	0.119680

PLOT 16 PROFILE 2

TIME AFTER INITIATION OF DRAINAGE DAYS	SOIL DEPTH, cm 15			30		
	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.005	0.140000	-5.000	.	0.178800	-2.410	.
0.153	0.120768	-19.520	.	0.155888	-20.465	7.711402
0.259	0.095900	-37.445	.	0.126652	-41.410	2.600445
0.896	0.080186	-48.890	.	0.108781	-51.250	0.850104
1.062	0.068918	-58.030	.	0.095851	-59.175	0.415777
1.269	0.066512	-60.285	.	0.093052	-61.190	0.346144
2.066	0.062104	-64.595	.	0.087898	-65.150	0.241591
2.273	0.058309	-68.365	.	0.083450	-68.660	0.179264
3.086	0.055815	-70.960	.	0.080510	-71.185	0.143602
3.283	0.053551	-73.345	.	0.077837	-73.520	0.117788
4.288	0.051596	-75.475	.	0.075516	-75.705	0.097321
5.273	0.048831	-78.540	.	0.072225	-78.930	0.073678
6.295	0.046666	-81.030	.	0.069633	-81.650	0.058118
7.241	0.044932	-83.085	.	0.067545	-83.975	0.047396
8.287	0.043476	-84.865	.	0.065782	-86.065	0.039362
10.291	0.041696	-87.140	.	0.063607	-88.850	0.030571
12.287	0.039793	-89.690	.	0.061261	-92.080	0.022723
14.296	0.038308	-91.820	.	0.059403	-94.885	0.017411
18.254	0.036693	-94.380	.	0.057336	-98.385	0.012275

PLOT 16 PROFILE 2 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 15 THETA cm3/cm3	PHEAD cm	K cm/day	SOIL DEPTH, cm 30 THETA cm3/cm3	PHEAD cm	K cm/day
21.287	0.035217	-96.955	.	0.055402	-101.970	0.008369
24.271	0.034312	-98.800	.	0.054166	-104.555	0.006145
29.272	0.033488	-100.865	.	0.052966	-107.365	0.004146
38.270	0.032691	-103.815	.	0.051625	-110.955	0.001975
42.248	0.032300	-106.190	.	0.050790	-113.445	0.000659

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	SOIL DEPTH, cm 60 THETA cm3/cm3	PHEAD cm	K cm/day
0.005	0.186500	-4.000	.	0.179300	-4.450	.
0.153	0.168227	-22.750	10.748120	0.163620	-22.515	16.090300
0.259	0.141699	-43.890	4.591851	0.139962	-43.440	7.884701
0.896	0.122918	-51.915	1.439784	0.119167	-53.040	1.910039
1.062	0.111231	-58.320	0.718339	0.105067	-60.705	0.775050
1.269	0.108881	-59.900	0.608132	0.102532	-62.595	0.621060
2.066	0.104561	-62.920	0.446133	0.098277	-66.210	0.406191
2.273	0.100835	-65.565	0.349414	0.094749	-69.375	0.285781
3.086	0.098386	-67.385	0.296137	0.092666	-71.555	0.222297
3.283	0.096166	-69.050	0.257494	0.090812	-73.555	0.177717
4.288	0.094261	-70.545	0.228351	0.089317	-75.340	0.144479
5.273	0.091584	-72.700	0.195777	0.087262	-77.915	0.107472
6.295	0.089510	-74.440	0.176280	0.085720	-80.000	0.084159
7.241	0.087867	-75.875	0.164887	0.084517	-81.720	0.068540
8.287	0.086504	-77.125	0.158790	0.083527	-83.215	0.057152
10.291	0.084858	-78.720	0.158188	0.082329	-85.125	0.044980
12.287	0.083115	-80.505	0.173876	0.081048	-87.265	0.034151
14.296	0.081764	-82.000	0.224495	0.080035	-89.050	0.026889
18.254	0.080274	-83.800	0.853456	0.078885	-91.200	0.019835
21.287	0.078862	-85.605	-0.189010	0.077775	-93.365	0.014388
24.271	0.077905	-86.895	-0.075520	0.077019	-94.910	0.011273
29.272	0.076835	-88.340	-0.036640	0.076209	-96.640	0.008461
38.270	0.075127	-90.410	-0.015780	0.075103	-99.115	0.005496
42.248	0.073550	-92.075	-0.008160	0.074240	-101.110	0.003882

PLOT 16 PROFILE 2 -- continued

TIME AFTER INITIATION OF DRAINAGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	75 PHEAD cm	75 K cm/day	90 THETA cm3/cm3	90 PHEAD cm	90 K cm/day
0.005	0.175600	.	.	0.165500	-18.980	.
0.153	0.160322	.	.	0.157632	-27.185	18.465760
0.259	0.136394	.	.	0.141251	-36.300	16.312300
0.896	0.115445	.	.	0.118488	-42.065	5.156131
1.062	0.101928	.	.	0.102748	-47.830	2.398839
1.269	0.099501	.	.	0.099783	-49.745	1.933007
2.066	0.095281	.	.	0.094692	-53.745	1.254603
2.273	0.091720	.	.	0.090426	-57.360	0.871982
3.086	0.089490	.	.	0.087828	-60.055	0.666360
3.283	0.087480	.	.	0.085502	-62.560	0.523980
4.288	0.085788	.	.	0.083585	-64.900	0.417670
5.273	0.083419	.	.	0.080924	-68.335	0.301909
6.295	0.081591	.	.	0.078895	-71.195	0.230668
7.241	0.080142	.	.	0.077296	-73.605	0.183927
8.287	0.078936	.	.	0.075969	-75.730	0.150540
10.291	0.077475	.	.	0.074355	-78.485	0.115687
12.287	0.075925	.	.	0.072632	-81.610	0.085545
14.296	0.074727	.	.	0.071280	-84.255	0.065846
18.254	0.073441	.	.	0.069789	-87.485	0.047205
21.287	0.072279	.	.	0.068406	-90.770	0.033200
24.271	0.071581	.	.	0.067538	-93.145	0.025340
29.272	0.070962	.	.	0.066727	-95.820	0.018309
38.270	0.070406	.	.	0.065942	-99.680	0.010893
42.248	0.070174	.	.	0.065577	-102.810	0.006762

TIME AFTER INITIATION OF DRAINAGE DAYS	SOIL DEPTH, cm 105 THETA, cm3/cm3	120	135
0.153	0.149259	0.153619	.
0.259	0.142130	0.146450	.
0.896	0.123499	0.137054	.
1.062	0.110486	0.133845	.
1.269	0.107403	0.131620	0.193013
2.066	0.101593	0.126032	0.191297
2.273	0.096540	0.120699	0.187966

PLOT 16 PROFILE 2 -- continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 105	120	135
	THETA, cm3/cm3		
3.086	0.093155	0.116323	0.180078
3.283	0.090074	0.112211	0.172411
4.288	0.087401	0.108263	0.164761
5.273	0.083624	0.102447	0.153529
6.295	0.080675	0.097601	0.144269
7.241	0.078326	0.093552	0.136619
8.287	0.076370	0.090035	0.130039
10.291	0.074011	0.085586	0.121786
12.287	0.071532	0.080712	0.112783
14.296	0.069650	0.076828	0.105608
18.254	0.067707	0.072601	0.097710
21.287	0.066030	0.068843	0.090534
24.271	0.065116	0.066758	0.086314
29.272	0.064448	0.065361	0.082982
38.270	0.064220	0.065764	0.081736
42.248	0.064513	0.067887	0.083356

PLOT 16 PROFILE 3

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 15 THETA cm3/cm3	PHEAD cm	K cm/day	30 THETA cm3/cm3	PHEAD cm	K cm/day
0.007	0.122200	-6.250	.	0.160500	-2.990	.
0.160	0.105335	-22.970	.	0.141438	-21.485	7.609327
0.262	0.086135	-42.415	.	0.117032	-42.975	1.750671
0.900	0.073569	-52.015	.	0.101718	-53.460	0.872011
1.068	0.062130	-59.855	.	0.090498	-61.990	0.380877
1.274	0.059761	-61.825	.	0.087979	-64.100	0.300640
2.071	0.055809	-65.630	.	0.083322	-68.120	0.189787
2.280	0.052533	-68.995	.	0.079284	-71.650	0.128509
3.094	0.050630	-71.375	.	0.076630	-74.085	0.097634
3.287	0.048953	-73.555	.	0.074240	-76.305	0.076483
4.300	0.047616	-75.575	.	0.072195	-78.305	0.061271
5.276	0.045791	-78.520	.	0.069342	-81.180	0.044866
6.300	0.044439	-80.965	.	0.067169	-83.495	0.035000
7.246	0.043383	-83.055	.	0.065460	-85.420	0.028571
8.292	0.042512	-84.910	.	0.064065	-87.090	0.024039
10.295	0.041452	-87.370	.	0.062421	-89.220	0.019369
12.291	0.040304	-90.235	.	0.060727	-91.610	0.015368
14.300	0.039374	-92.745	.	0.059468	-93.605	0.012820
18.259	0.038273	-95.965	.	0.058171	-96.005	0.010527
21.291	0.037164	-99.380	.	0.057019	-98.425	0.008934
24.275	0.036358	-102.005	.	0.056313	-100.155	0.008219
29.276	0.035426	-105.155	.	0.055593	-102.085	0.007853
38.275	0.034009	-110.120	.	0.054502	-104.850	0.008375
42.252	0.032805	-114.425	.	0.053485	-107.080	0.010128

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
0.007	0.175930	-1.540	.	0.170600	-5.610	.
0.160	0.155934	-19.555	12.280360	0.157010	-22.945	11.42410
0.262	0.132714	-40.485	3.688284	0.136676	-43.085	3.871072
0.900	0.121486	-50.695	1.690138	0.119283	-52.910	1.583313
1.068	0.112385	-59.000	0.805188	0.107532	-60.905	0.746331
1.274	0.110163	-61.055	0.653147	0.105348	-62.885	0.607088

PLOT 16 PROFILE 3--continued

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm					
	45			60		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
2.071	0.105976	-64.965	0.433961	0.101520	-66.655	0.406252
2.280	0.102316	-68.395	0.307475	0.098262	-69.965	0.289929
3.094	0.099846	-70.760	0.239893	0.096188	-72.250	0.227441
3.287	0.097608	-72.915	0.192442	0.094325	-74.330	0.183410
4.300	0.095643	-74.845	0.156835	0.092730	-76.200	0.149960
5.276	0.092860	-77.610	0.117293	0.090487	-78.895	0.112498
6.300	0.090678	-79.830	0.092455	0.088745	-81.070	0.088790
7.246	0.088916	-81.665	0.075720	0.087341	-82.875	0.072666
8.292	0.087437	-83.235	0.063672	0.086163	-84.435	0.060860
10.295	0.085629	-85.215	0.050863	0.084714	-86.435	0.048139
12.291	0.083698	-87.400	0.039537	0.083151	-88.675	0.036747
14.300	0.082195	-89.170	0.032077	0.081914	-90.540	0.029045
18.259	0.080573	-91.185	0.025094	0.080532	-92.795	0.021485
21.291	0.079103	-93.095	0.019975	0.079235	-95.060	0.015683
24.275	0.078218	-94.325	0.017374	0.078398	-96.680	0.012391
29.276	0.077434	-95.490	0.015560	0.077574	-98.495	0.009435
38.275	0.076736	-96.625	0.015588	0.076623	-101.085	0.006429
42.252	0.076452	-97.145	0.019066	0.076004	-103.170	0.004924

TIME AFTER INITIATION OF DRAIN-AGE	SOIL DEPTH, cm					
	75			90		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.007	0.172212	.	.	0.166500	-17.408	.
0.160	0.151079	.	.	0.156625	-25.441	18.90278
0.262	0.126545	.	.	0.138579	-35.756	10.23648
0.900	0.114727	.	.	0.116291	-44.258	3.927928
1.068	0.105163	.	.	0.100736	-51.381	1.865097
1.274	0.102841	.	.	0.097914	-53.224	1.521484
2.071	0.098488	.	.	0.093182	-56.789	1.022744
2.280	0.094693	.	.	0.089241	-59.940	0.732758
3.094	0.092157	.	.	0.086901	-62.143	0.575807
3.287	0.089864	.	.	0.084828	-64.155	0.464780
4.300	0.087876	.	.	0.083144	-65.981	0.380188
5.276	0.085080	.	.	0.080828	-68.614	0.285491
6.300	0.082920	.	.	0.079095	-70.750	0.225409

PLOT 16 PROFILE 3--continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
7.246	0.081203	.	.	0.077733	-72.530	0.184442
8.292	0.079787	.	.	0.076610	-74.076	0.154388
10.295	0.078101	.	.	0.075249	-76.059	0.122125
12.291	0.076355	.	.	0.073792	-78.286	0.093122
14.300	0.075062	.	.	0.072638	-80.151	0.073424
18.259	0.073787	.	.	0.071324	-82.402	0.054147
21.291	0.072750	.	.	0.070055	-84.671	0.039092
24.275	0.072259	.	.	0.069188	-86.298	0.030421
29.276	0.072021	.	.	0.068256	-88.120	0.022480
38.275	0.072318	.	.	0.066983	-90.730	0.014017
42.252	0.072977	.	.	0.065989	-92.835	0.009335

TIME AFTER INITIATION OF DRAINA-GE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm3/cm3			
0.160	0.149467	0.144490	.	.
0.262	0.141599	0.140320	.	.
0.900	0.119287	0.125717	.	.
1.068	0.103270	0.113837	0.145229	.
1.274	0.100159	0.110901	0.144029	.
2.071	0.094766	0.105310	0.142577	0.212583
2.280	0.090208	0.100398	0.141597	0.214541
3.094	0.087382	0.097019	0.137298	0.214692
3.287	0.084858	0.093941	0.132861	0.211746
4.300	0.082744	0.091183	0.127810	0.204253
5.276	0.079798	0.087230	0.120263	0.192352
6.300	0.077545	0.084060	0.113969	0.181820
7.246	0.075751	0.081447	0.108748	0.172864
8.292	0.074257	0.079205	0.104290	0.165072
10.295	0.072437	0.076386	0.098738	0.155183
12.291	0.070492	0.073289	0.092697	0.144261
14.300	0.068970	0.070788	0.087862	0.135387
18.259	0.067310	0.067954	0.082393	0.125253
21.291	0.065795	0.065288	0.077203	0.115641
24.275	0.064879	0.063600	0.073817	0.109454

PLOT 16 PROFILE 3--continued

TIME AFTER INITIATION OF DRAINAGE DAYS	SOIL DEPTH, cm 105	120	135	150
	THETA, cm3/cm3			
29.276	0.064088	0.062042	0.070467	0.103582
38.275	0.063516	0.060656	0.066693	0.097844
42.252	0.063463	0.060165	0.064380	0.095202

PLOT 16 PROFILE 4

TIME AFTER INITIATION OF DRAINAGE	SOIL DEPTH, cm 15			30		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.009	0.123893	-7.090	.	0.164303	-4.000	.
0.167	0.106279	-24.490	.	0.142697	-22.195	8.344510
0.269	0.085804	-44.745	.	0.117582	-43.620	1.922575
0.905	0.075728	-54.955	.	0.105217	-53.365	0.804630
1.075	0.067503	-63.370	.	0.095122	-60.685	0.458694
1.280	0.065476	-65.515	.	0.092632	-62.290	0.401087
2.076	0.061680	-69.655	.	0.087966	-65.340	0.310903
2.284	0.058361	-73.325	.	0.083887	-68.050	0.254053
3.099	0.056123	-75.935	.	0.081133	-70.075	0.216977
3.292	0.054094	-78.335	.	0.078636	-71.970	0.188877
4.303	0.052326	-80.560	.	0.076457	-73.870	0.162950
5.280	0.049827	-83.815	.	0.073374	-76.780	0.129981
6.303	0.047878	-86.530	.	0.070965	-79.405	0.105013
7.250	0.046314	-88.855	.	0.069029	-81.800	0.085826
8.297	0.045009	-90.940	.	0.067410	-84.065	0.070447
10.300	0.043431	-93.715	.	0.065448	-87.260	0.052991
12.290	0.041770	-96.945	.	0.063374	-91.140	0.037227
14.300	0.040501	-99.795	.	0.061782	-94.680	0.026855
18.260	0.039173	-103.490	.	0.060101	-99.310	0.017297
21.290	0.038014	-107.425	.	0.058617	-104.130	0.010562
24.280	0.037366	-110.475	.	0.057768	-107.600	0.007003
29.280	0.036865	-114.165	.	0.057082	-111.210	0.003962
38.280	0.036610	-120.015	.	0.056644	-114.995	0.000360
42.250	0.036706	-125.110	.	0.056646	-116.760	-0.003710

PLOT 16 PROFILE 4--continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
0.009	0.183100	-4.390	.	0.172700	-14.680	.
0.167	0.161519	-23.455	10.302380	0.156844	-30.500	10.01715
0.269	0.135870	-45.635	2.550215	0.131594	-48.905	4.000470
0.905	0.121719	-56.665	0.955729	0.113242	-58.060	1.477649
1.075	0.110261	-65.705	0.454971	0.103300	-65.560	0.823252
1.280	0.107516	-67.970	0.367507	0.101334	-67.435	0.703986
2.076	0.102501	-72.265	0.242529	0.097689	-71.000	0.516943
2.284	0.098171	-76.045	0.170927	0.094510	-74.140	0.399360
3.099	0.095391	-78.660	0.133067	0.092372	-76.310	0.329236
3.292	0.092901	-81.045	0.106605	0.090433	-78.290	0.277288
4.303	0.090849	-83.190	0.087057	0.088741	-80.070	0.235030
5.280	0.088044	-86.275	0.065384	0.086346	-82.630	0.184987
6.303	0.085998	-88.765	0.051965	0.084474	-84.695	0.151061
7.250	0.084460	-90.835	0.042991	0.082968	-86.410	0.126749
8.297	0.083266	-92.630	0.036445	0.081708	-87.900	0.107920
10.300	0.081961	-94.920	0.029570	0.080178	-89.800	0.086852
12.290	0.080723	-97.485	0.023338	0.078558	-91.930	0.066923
14.300	0.079906	-99.625	0.019093	0.077311	-93.710	0.052754
18.260	0.079179	-102.210	0.014828	0.075988	-95.855	0.038395
21.290	0.078579	-104.810	0.011230	0.074814	-98.010	0.026940
24.280	0.078184	-106.665	0.008913	0.074135	-99.550	0.020385
29.280	0.077596	-108.745	0.006451	0.073575	-101.275	0.014790
38.280	0.075939	-111.720	0.003203	0.073186	-103.745	0.010217
42.250	0.073827	-114.115	0.001449	0.073140	-105.730	0.009467

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.009	0.168000	.	.	0.164400	-18.080	.
0.167	0.153962	.	.	0.154325	-27.960	21.68493
0.269	0.132757	.	.	0.136153	-39.505	13.91237
0.905	0.112930	.	.	0.113768	-45.675	4.701242
1.075	0.098950	.	.	0.097991	-50.875	2.481390
1.280	0.096381	.	.	0.095094	-52.300	2.091309
2.076	0.092097	.	.	0.090267	-55.190	1.485048

PLOT 16 PROFILE 4--continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
2.284	0.088526	.	.	0.086245	-57.810	1.111326
3.099	0.086404	.	.	0.083857	-59.835	0.884578
3.292	0.084524	.	.	0.081741	-61.730	0.719172
4.303	0.083003	.	.	0.080030	-63.610	0.583796
5.280	0.080911	.	.	0.077679	-66.455	0.427694
6.303	0.079347	.	.	0.075920	-68.965	0.325211
7.250	0.078119	.	.	0.074542	-71.200	0.255038
8.297	0.077108	.	.	0.073406	-73.265	0.203626
10.300	0.075885	.	.	0.072035	-76.110	0.149639
12.290	0.074580	.	.	0.070571	-79.490	0.103794
14.300	0.073548	.	.	0.069413	-82.500	0.074843
18.260	0.072373	.	.	0.068097	-86.325	0.049026
21.290	0.071240	.	.	0.066828	-90.235	0.031366
24.280	0.070468	.	.	0.065964	-93.000	0.022491
29.280	0.069640	.	.	0.065037	-95.830	0.015573
38.280	0.068510	.	.	0.063774	-98.780	0.010002
42.250	0.067630	.	.	0.062790	-100.180	0.008150

PLOT 16 PROFILE 5

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 15 THETA cm3/cm3	PHEAD cm	K cm/day	30 THETA cm3/cm3	PHEAD cm	K cm/day
0.012	0.139562	-5.130	.	0.172202	-3.410	.
0.169	0.117528	-22.095	.	0.148929	-18.740	10.99891
0.273	0.091548	-42.160	.	0.121459	-36.885	3.567653
0.911	0.077927	-53.145	.	0.106822	-46.945	1.581560
1.080	0.066935	-62.165	.	0.094931	-55.245	0.890182
1.284	0.064299	-64.465	.	0.092013	-57.390	0.754801
2.081	0.059437	-68.940	.	0.086520	-61.620	0.538720
2.287	0.055231	-72.910	.	0.081721	-65.395	0.402966
3.103	0.052511	-75.750	.	0.078494	-68.145	0.321616
3.296	0.050065	-78.370	.	0.075564	-70.690	0.261668
4.308	0.048033	-80.805	.	0.073019	-73.090	0.213557
5.284	0.045242	-84.375	.	0.069433	-76.640	0.157454
6.307	0.043184	-87.365	.	0.066650	-79.650	0.120612

PLOT 16 PROFILE 5--continued

TIME AFTER INITIATION OF DRAINAGE	SOIL DEPTH, cm 15			30		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
7.254	0.041617	-89.940	.	0.064425	-82.260	0.095069
8.301	0.040384	-92.250	.	0.062580	-84.615	0.076360
10.300	0.039005	-95.335	.	0.060369	-87.765	0.056520
12.300	0.037658	-98.960	.	0.058057	-91.455	0.039348
14.310	0.036726	-102.175	.	0.056317	-94.695	0.028498
18.270	0.035837	-106.360	.	0.054554	-98.790	0.019228
21.300	0.035062	-110.840	.	0.053066	-103.020	0.013439
24.280	0.034541	-114.320	.	0.052295	-106.110	0.011486
29.280	0.033832	-118.565	.	0.051795	-109.545	0.012006
38.280	0.032098	-125.355	.	0.051826	-114.105	0.023830
42.260	0.030014	-131.295	.	0.052341	-117.415	0.109229

TIME AFTER INITIATION OF DRAINAGE	SOIL DEPTH, cm 45			60		
DAYS	THETA cm3/cm3	PHEAD cm	K cm/day	THETA cm3/cm3	PHEAD cm	K cm/day
0.012	0.179891	-6.210	.	0.163500	-11.440	.
0.169	0.158420	-20.795	11.269680	0.150031	-25.330	12.40220
0.273	0.133095	-38.035	3.226973	0.130548	-41.735	3.928591
0.911	0.119745	-47.395	1.355875	0.114285	-50.580	1.534881
1.080	0.108947	-55.055	0.733192	0.102894	-57.805	0.795028
1.284	0.106337	-56.980	0.619733	0.100639	-59.605	0.664580
2.081	0.101489	-60.695	0.445716	0.096618	-63.045	0.466476
2.287	0.097281	-63.980	0.337840	0.093173	-66.080	0.345490
3.103	0.094522	-66.290	0.276280	0.090949	-68.180	0.276665
3.296	0.092032	-68.410	0.230777	0.088941	-70.095	0.226383
4.308	0.089930	-70.345	0.195372	0.087221	-71.820	0.187160
5.284	0.087015	-73.155	0.153995	0.084801	-74.300	0.141746
6.307	0.084824	-75.465	0.126870	0.082923	-76.300	0.112116
7.254	0.083125	-77.420	0.107781	0.081414	-77.965	0.091452
8.301	0.081759	-79.140	0.093597	0.080150	-79.405	0.076077
10.300	0.080190	-81.390	0.078032	0.078610	-81.245	0.059350
12.300	0.078614	-83.975	0.063737	0.076963	-83.310	0.044183
14.310	0.077486	-86.205	0.054061	0.075674	-85.035	0.033930
18.270	0.076390	-89.015	0.045068	0.074270	-87.115	0.024271
21.300	0.075461	-91.945	0.039465	0.072984	-89.205	0.017259

PLOT 16 PROFILE 5--continued

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 45 THETA cm3/cm3	PHEAD cm	K cm/day	60 THETA cm3/cm3	PHEAD cm	K cm/day
24.280	0.074920	-94.145	0.038771	0.072191	-90.700	0.013914
29.280	0.074360	-96.735	0.043767	0.071458	-92.370	0.012067
38.280	0.073363	-100.715	0.062212	0.070724	-94.760	0.013861
42.260	0.072295	-104.100	0.076646	0.070339	-96.690	0.020322

TIME AFTER INITIATION OF DRAIN-AGE DAYS	SOIL DEPTH, cm 75 THETA cm3/cm3	PHEAD cm	K cm/day	90 THETA cm3/cm3	PHEAD cm	K cm/day
0.012	0.170500	.	.	0.159800	-18.327	.
0.169	0.155330	.	.	0.151840	-22.479	23.31333
0.273	0.130507	.	.	0.136043	-28.932	16.88662
0.911	0.109950	.	.	0.114332	-37.987	5.068041
1.080	0.097966	.	.	0.098991	-45.776	2.277274
1.284	0.095829	.	.	0.096126	-47.881	1.840045
2.081	0.091989	.	.	0.091272	-52.007	1.208779
2.287	0.088688	.	.	0.087207	-55.674	0.846684
3.103	0.086542	.	.	0.084762	-58.273	0.651071
3.296	0.084604	.	.	0.082583	-60.660	0.513303
4.308	0.082952	.	.	0.080804	-62.833	0.410192
5.284	0.080641	.	.	0.078349	-65.976	0.295855
6.307	0.078870	.	.	0.076497	-68.536	0.224778
7.254	0.077464	.	.	0.075035	-70.677	0.177326
8.301	0.076302	.	.	0.073823	-72.542	0.143257
10.300	0.074906	.	.	0.072349	-74.935	0.107665
12.300	0.073427	.	.	0.070763	-77.630	0.077004
14.310	0.072271	.	.	0.069498	-79.894	0.057323
18.270	0.070966	.	.	0.068050	-82.630	0.039565
21.300	0.069686	.	.	0.066646	-85.390	0.027292
24.280	0.068759	.	.	0.065683	-87.370	0.021394
29.280	0.067618	.	.	0.064643	-89.591	0.017384
38.280	0.065539	.	.	0.063212	-92.779	0.015938
42.260	0.063460	.	.	0.062090	-95.354	0.017659

APPENDIX B
HYDRODYNAMIC CHARACTERISTICS OF SOIL IN UNIT 2, DETERMINED ON 3-cm UNDISTURBED CORE SAMPLES PLOTS 9 AND 16, IREP, GAINASVILLE

PLOT 09, PROFILE 1

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.52	1.65	1.64	1.59	1.58	1.59
Ks (cm/hr)	16.40	23.00	32.20	36.20	36.20	28.30
SUCTION (cm)						
3.5	0.4082	0.3361	0.3841	0.3791	0.3848	0.3673
20.0	0.4071	0.3147	0.3833	0.3784	0.3762	0.3633
30.0	0.4034	0.2951	0.2577	0.2527	0.3202	0.3486
45.0	0.2513	0.1743	0.1505	0.1455	0.1715	0.1810
60.0	0.1549	0.1139	0.1116	0.1066	0.1058	0.1125
80.0	0.1213	0.0885	0.0877	0.0827	0.0795	0.0846
100.0	0.1064	0.0738	0.0741	0.0691	0.0660	0.0700
150.0	0.0898	0.0597	0.0593	0.0543	0.0522	0.0558
200.0	0.0825	0.0533	0.0533	0.0484	0.0457	0.0492
345.0	0.0716	0.0459	0.0448	0.0399	0.0393	0.0384
15000.0	0.0146	0.0131	0.0143	0.0130	0.0110	0.0085

PLOT 09, PROFILE 2

	SOIL DEPTH,cm					
	15	30	45	60	75	90
BD (g/cm3)	1.53	1.62	1.64	1.58	1.59	1.59
Ks (cm/hr)	29.60	28.90	27.60	32.20	30.90	28.30
SUCTION (cm)						
3.5	0.3997	0.3591	0.3734	0.3775	0.3661	0.3617
20.0	0.3988	0.3547	0.3627	0.3714	0.3598	0.3556
30.0	0.3852	0.3437	0.3462	0.3248	0.2895	0.3548

PLOT 09, PROFILE 2--continued

	SOIL DEPTH, cm					
	15	30	45	60	75	90
SUCTION (cm)						
45.0	0.1963	0.1956	0.2111	0.1744	0.1505	0.1532
60.0	0.1281	0.1202	0.1173	0.1128	0.0996	0.0979
80.0	0.1020	0.0920	0.0865	0.0868	0.0763	0.0730
100.0	0.0887	0.0774	0.0735	0.0722	0.0635	0.0595
150.0	0.0745	0.0627	0.0589	0.0583	0.0504	0.0460
200.0	0.0678	0.0558	0.0510	0.0511	0.0441	0.0399
345.0	0.0568	0.0497	0.0451	0.0476	0.0408	0.0329
15000.0	0.0141	0.0146	0.0138	0.0125	0.0105	0.0090

PLOT 9 PROFILE 3

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.59	1.65	1.6	1.56	1.59	1.63
Ks (cm/hr)	36.20	19.70	23.00	32.20	32.20	33.50
SUCTION (cm)						
3.5	0.3336	0.3681	0.3716	0.3741	0.3731	0.4093
20.0	0.3251	0.3595	0.3654	0.3607	0.3709	0.3841
30.0	0.2879	0.3519	0.3404	0.2789	0.3329	0.3795
45.0	0.1338	0.2074	0.1768	0.1601	0.1781	0.1874
60.0	0.0976	0.1237	0.1192	0.1072	0.1017	0.1055
80.0	0.0792	0.0951	0.0929	0.0850	0.0752	0.0754
100.0	0.0672	0.0805	0.0796	0.0700	0.0606	0.0606
150.0	0.0560	0.0678	0.0643	0.0600	0.0478	0.0470
200.0	0.0507	0.0597	0.0573	0.0520	0.0412	0.0400
345.0	0.0450	0.0504	0.0494	0.0463	0.0386	0.0333
15000.0	0.0118	0.0131	0.0116	0.0119	0.0086	0.0078

PLOT 9 PROFILE 4

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.60	1.64	1.66	1.59	1.60	1.61
Ks (cm/hr)	28.90	23.00	30.20	37.50	32.90	34.80

PLOT 9 PROFILE 4--continued

	SOIL DEPTH, cm					
	15	30	45	60	75	90
SUCTION (cm)						
3.5	0.3633	0.3604	0.3345	0.3671	0.3642	0.3817
20.0	0.3525	0.3553	0.3094	0.3610	0.3483	0.3754
30.0	0.3302	0.3532	0.2723	0.2968	0.2974	0.2704
45.0	0.2069	0.2348	0.1766	0.1811	0.1681	0.1246
60.0	0.1157	0.1239	0.1201	0.1069	0.1007	0.0897
80.0	0.0894	0.0919	0.0919	0.0789	0.0757	0.0669
100.0	0.0748	0.0774	0.0784	0.0643	0.0630	0.0538
150.0	0.0630	0.0725	0.0697	0.0545	0.0492	0.0408
200.0	0.0560	0.0640	0.0635	0.0498	0.0456	0.0343
345.0	0.0479	0.0492	0.0507	0.0380	0.0358	0.0266
15000.0	0.0139	0.0143	0.0134	0.0110	0.0104	0.0060

PLOT 9 PROFILE 5

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.60	1.66	1.58	1.58	1.57	1.61
Ks (cm/hr)	27.00	38.10	25.60	32.20	35.50	35.50
SUCTION (cm)						
3.5	0.3320	0.3473	0.3803	0.3395	0.3586	0.3068
20.0	0.3248	0.3425	0.3706	0.3369	0.3405	0.2825
30.0	0.1918	0.2187	0.2492	0.2878	0.2763	0.2733
45.0	0.1416	0.1572	0.1535	0.1525	0.1511	0.1449
60.0	0.1072	0.1157	0.1085	0.1012	0.1005	0.0928
80.0	0.0860	0.0904	0.0837	0.0774	0.0780	0.0704
100.0	0.0745	0.0771	0.0692	0.0652	0.0659	0.0592
150.0	0.0605	0.0630	0.0548	0.0519	0.0524	0.0451
200.0	0.0541	0.0533	0.0460	0.0432	0.0446	0.0362
345.0	0.0479	0.0488	0.0393	0.0380	0.0384	0.0326
15000.0	0.0133	0.0138	0.0116	0.0101	0.0103	0.0086

PLOT 16 PROFILE 1

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.61	1.67	1.51	1.62	1.66	1.67
Ks (cm/hr)	23.70	21.00	30.20	30.20	31.60	38.10
SUCTION (cm)						
3.5	0.3718	0.3658	0.4580	0.3683	0.3603	0.3686
20.0	0.3680	0.3628	0.4251	0.3676	0.3531	0.3633
30.0	0.3525	0.3626	0.3591	0.2726	0.3394	0.3518
45.0	0.2294	0.2577	0.2501	0.1401	0.1788	0.1699
60.0	0.1427	0.1557	0.2073	0.1015	0.1153	0.1077
80.0	0.1144	0.1170	0.1868	0.0812	0.0909	0.0825
100.0	0.0990	0.1055	0.1741	0.0685	0.0777	0.0685
150.0	0.0828	0.0888	0.1601	0.0564	0.0625	0.0555
200.0	0.0761	0.0814	0.1535	0.0484	0.0548	0.0485
345.0	0.0676	0.0728	0.0801	0.0431	0.0460	0.0421
15000.0	0.0155	0.0168	0.0157	0.0143	0.0133	0.0125

PLOT 16 PROFILE 2

	SOIL DEPTH,cm					
	15	30	45	60	75	90
BD (g/cm3)	1.68	1.64	1.64	1.58	1.66	1.67
Ks (cm/hr)	19.70	15.80	39.40	42.10	22.40	28.90
SUCTION (cm)						
3.5	0.3702	0.3258	0.3756	0.3867	0.2957	0.3557
20.0	0.3697	0.3177	0.3570	0.3687	0.2863	0.3508
30.0	0.3680	0.3056	0.2897	0.2776	0.2767	0.2754
45.0	0.2906	0.1879	0.1668	0.1518	0.1569	0.1613
60.0	0.1481	0.1275	0.1173	0.1053	0.1100	0.1150
80.0	0.1094	0.1028	0.0936	0.0843	0.0856	0.0878
100.0	0.0925	0.0898	0.0815	0.0709	0.0726	0.0736
150.0	0.0771	0.0746	0.0688	0.0570	0.0600	0.0616
200.0	0.0701	0.0676	0.0605	0.0511	0.0535	0.0533
345.0	0.0609	0.0570	0.0529	0.0443	0.0462	0.0454
15000.0	0.0165	0.0154	0.0155	0.0137	0.0138	0.0129

PLOT 16 PROFILE 3

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.58	1.73	1.68	1.59	1.59	1.57
Ks (cm/hr)	31.60	17.10	28.90	28.90	34.20	31.60
SUCTION (cm)						
3.5	0.3931	0.3420	0.3697	0.3680	0.3700	0.3772
20.0	0.3871	0.3299	0.3670	0.3659	0.3692	0.3744
30.0	0.3367	0.3110	0.3252	0.3455	0.2862	0.2964
45.0	0.1769	0.2431	0.2000	0.1543	0.1475	0.1509
60.0	0.1218	0.1351	0.1188	0.1058	0.1004	0.1037
80.0	0.0976	0.0979	0.0904	0.0843	0.0795	0.0820
100.0	0.0872	0.0828	0.0773	0.0736	0.0679	0.0701
150.0	0.0741	0.0692	0.0630	0.0608	0.0567	0.0587
200.0	0.0665	0.0606	0.0552	0.0539	0.0498	0.0513
345.0	0.0576	0.0517	0.0466	0.0472	0.0419	0.0438
15000.0	0.0141	0.0140	0.0176	0.0167	0.0143	0.0136

PLOT 16 PROFILE 4

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.67	1.63	1.62	1.61	1.61	1.57
Ks (cm/hr)	14.50	17.10	25.60	23.70	36.80	39.40
SUCTION (cm)						
3.5	0.3714	0.3716	0.3735	0.3652	0.3922	0.3918
20.0	0.3665	0.3673	0.3440	0.3635	0.3830	0.3763
30.0	0.3623	0.3487	0.3027	0.3423	0.2929	0.3123
45.0	0.2879	0.2343	0.1645	0.1670	0.1551	0.1587
60.0	0.1433	0.1291	0.1101	0.1097	0.1046	0.1071
80.0	0.1036	0.1018	0.0874	0.0881	0.0840	0.0896
100.0	0.0891	0.0862	0.0751	0.0768	0.0709	0.0741
150.0	0.0742	0.0730	0.0611	0.0609	0.0573	0.0612
200.0	0.0679	0.0660	0.0542	0.0554	0.0511	0.0548
345.0	0.0590	0.0583	0.0463	0.0466	0.0432	0.0450
15000.0	0.0155	0.0172	0.0151	0.0144	0.0135	0.0127

PLOT 16 PROFILE 5

	SOIL DEPTH, cm					
	15	30	45	60	75	90
BD (g/cm3)	1.66	1.68	1.64	1.62	1.63	1.62
Ks (cm/hr)	25.00	20.60	24.50	32.90	32.20	33.50
SUCTION (cm)						
3.5	0.3463	0.3271	0.3474	0.3714	0.3681	0.3747
20.0	0.3424	0.3160	0.3394	0.3654	0.3623	0.3714
30.0	0.3215	0.2871	0.2900	0.3172	0.3169	0.2771
45.0	0.1591	0.1874	0.1676	0.1626	0.1646	0.1626
60.0	0.1191	0.1310	0.1120	0.1096	0.1097	0.1099
80.0	0.0967	0.1033	0.0894	0.0856	0.0849	0.0846
100.0	0.0817	0.0881	0.0757	0.0732	0.0713	0.0719
150.0	0.0685	0.0741	0.0606	0.0595	0.0586	0.0583
200.0	0.0628	0.0673	0.0543	0.0541	0.0523	0.0538
345.0	0.0535	0.0577	0.0462	0.0466	0.0443	0.0431
15000.0	0.0152	0.0151	0.0150	0.0140	0.0134	0.0133

APPENDIX C
DAILY PRESSURE HEADS IN THE ROOT ZONE OF CORN, SORGHUM, AND PEANUT CROPS, GAINESVILLE, 1987

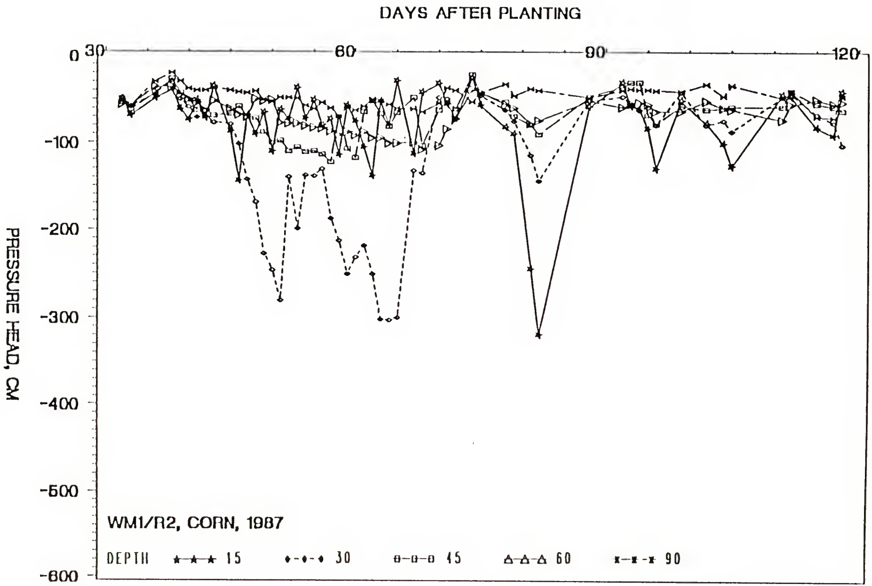


Fig. C-1. Daily pressure heads in the root zone of Pioneer 3165 corn, Gainesville, 1987.

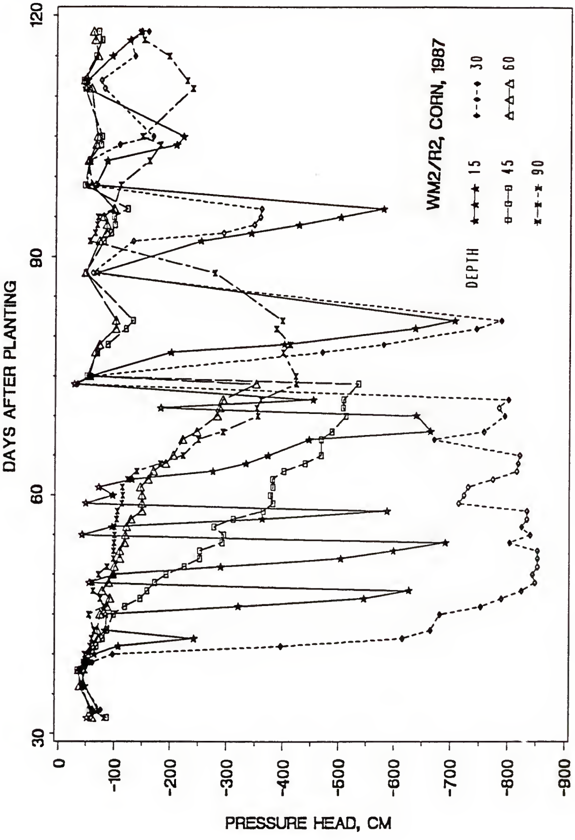


Fig. C-1.- Continued

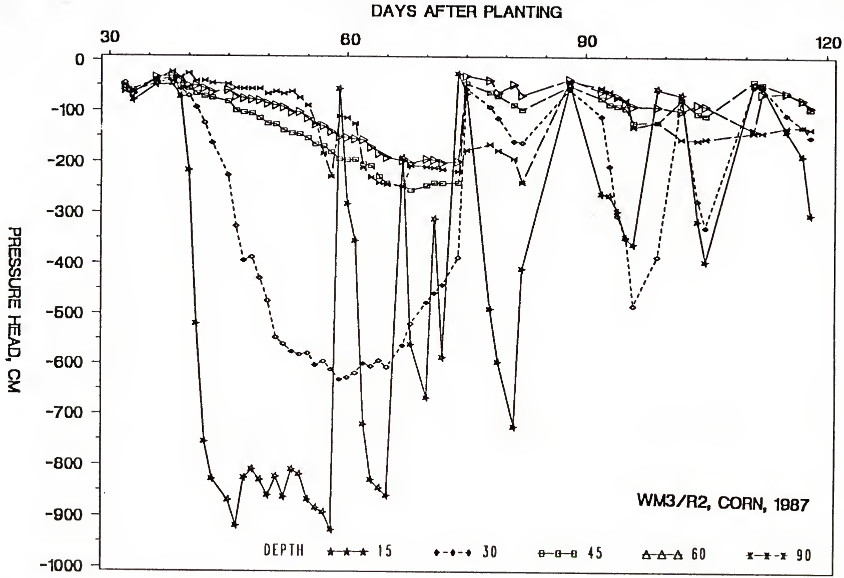


Fig. C-1.- Continued

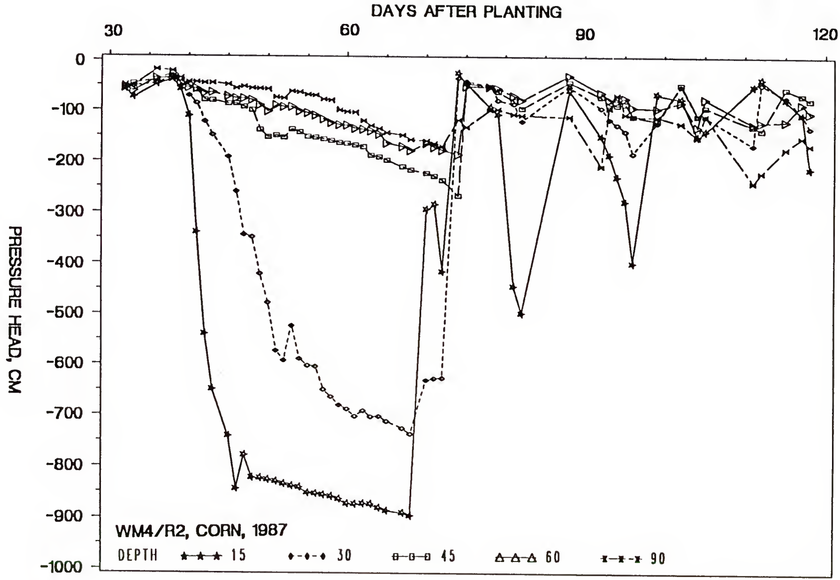


Fig. C-1.- Continued

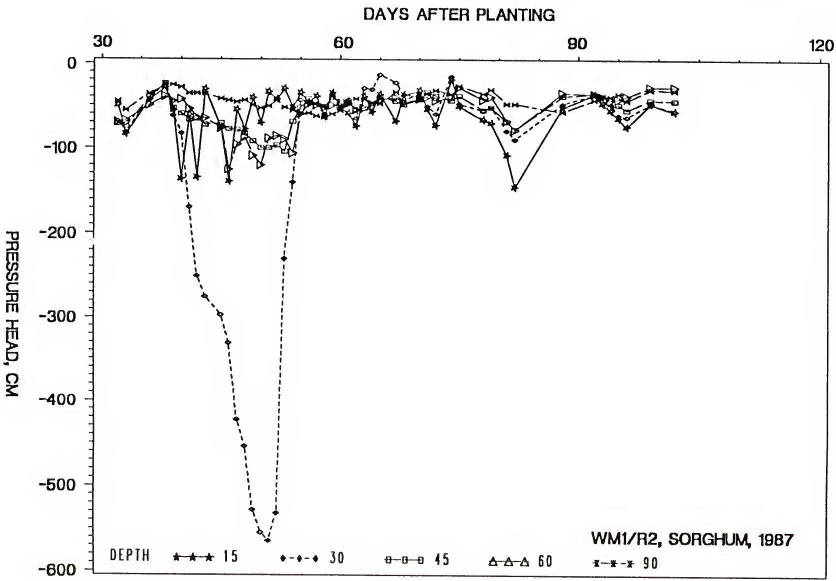


Fig. C-2. Daily pressure heads in the root zone of Northrup King Savanna 5 sorghum, Gainesville, 1987.

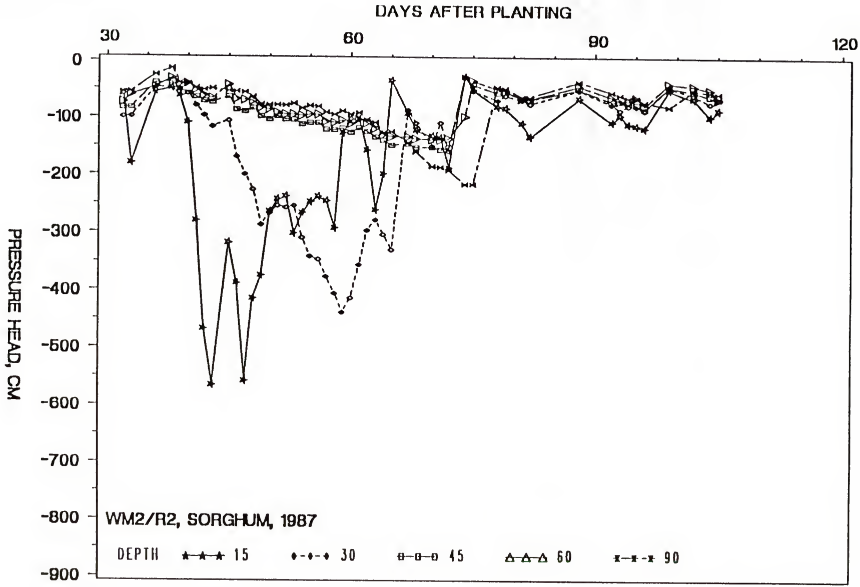


Fig. C-2.- Continued

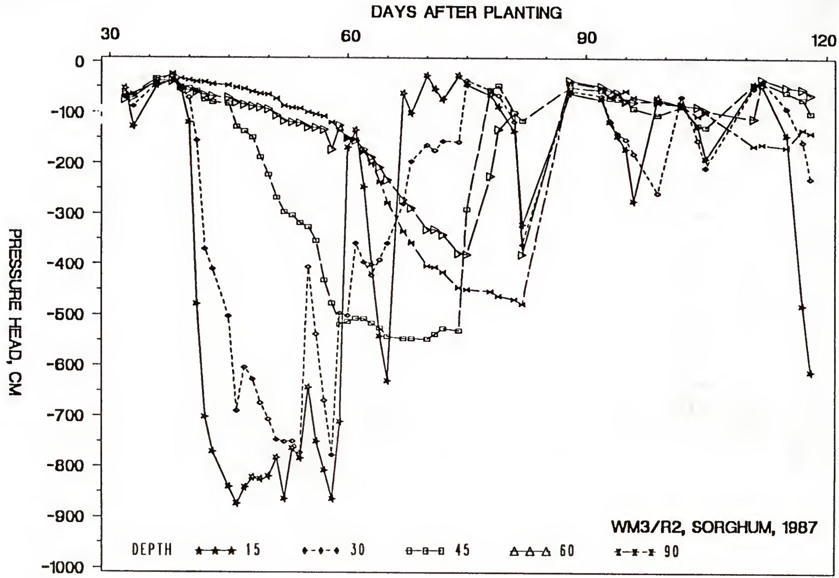


Fig. C-2.- Continued

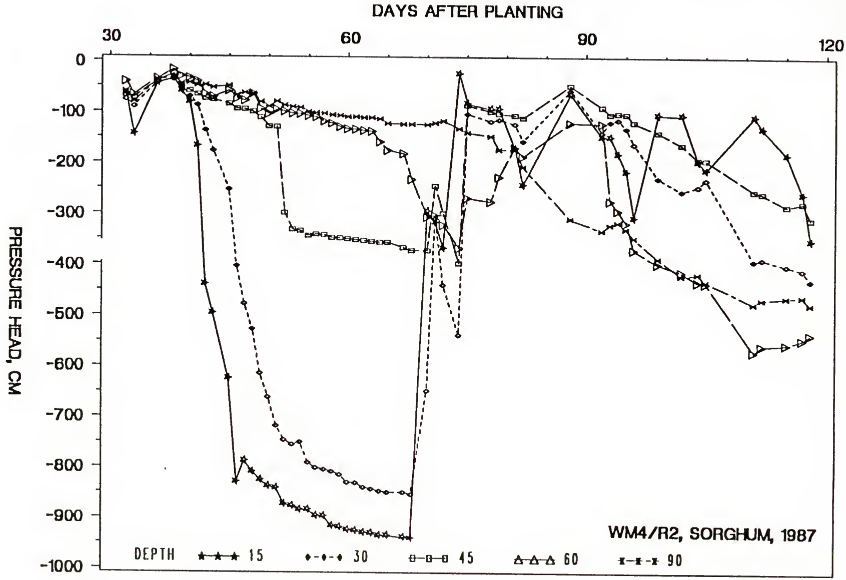


Fig. C-2.- Continued

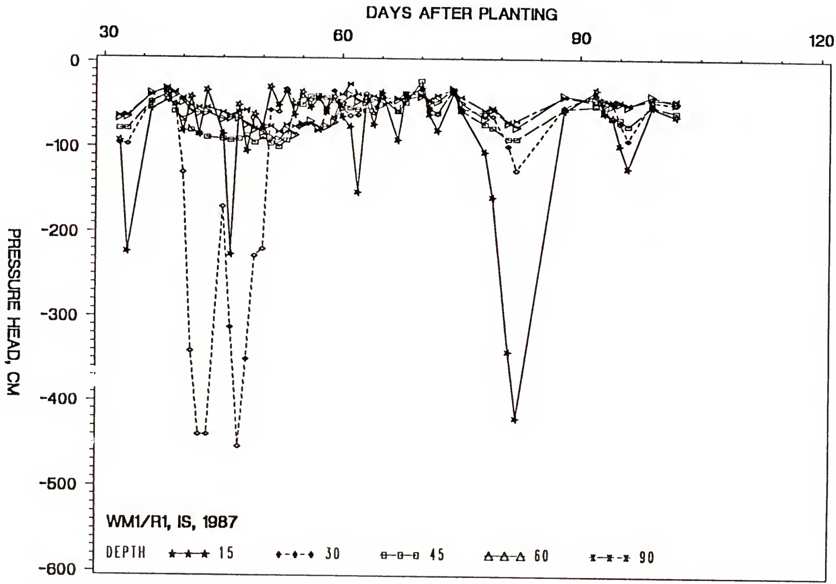


Fig. C-2.- Continued

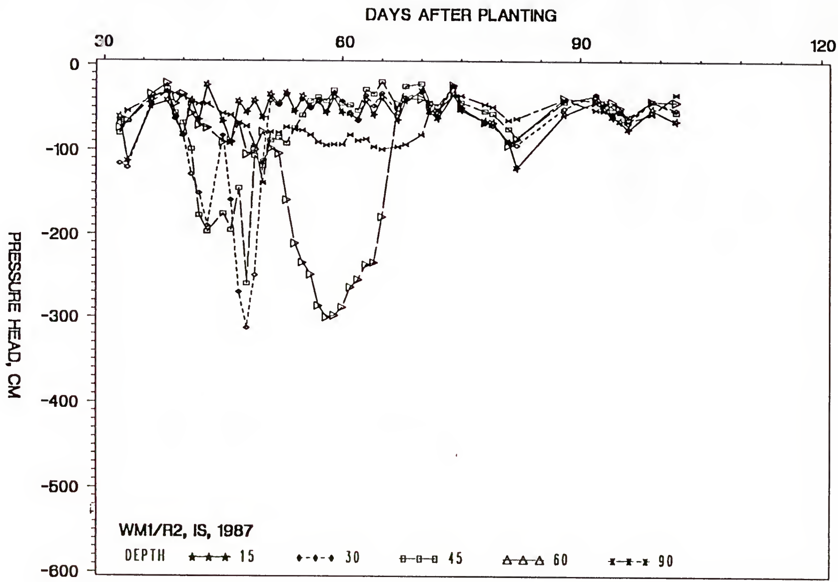


Fig. C-2.- Continued

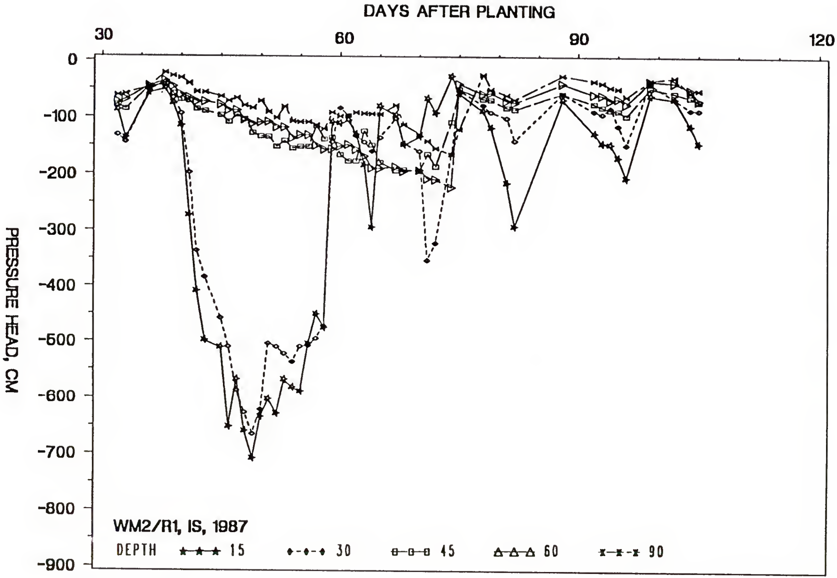


Fig. C-2.- Continued

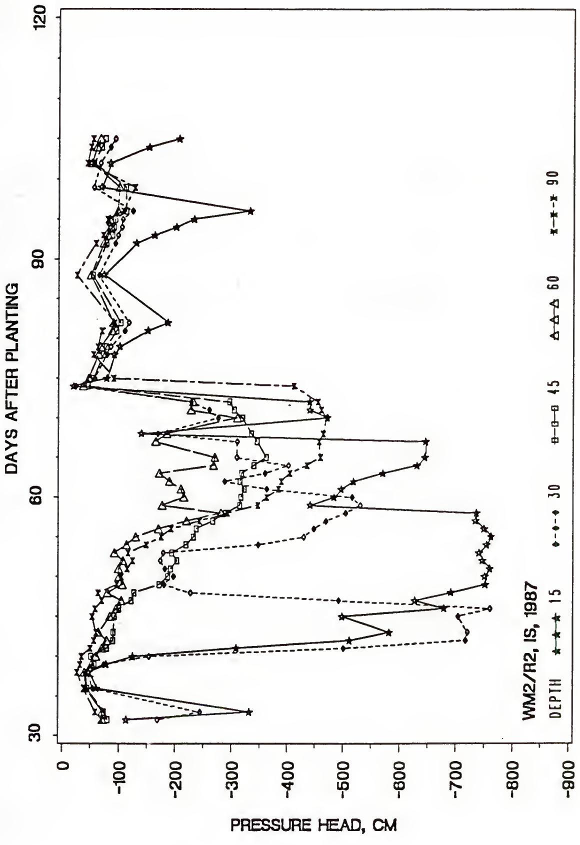


Fig. C-2.- Continued

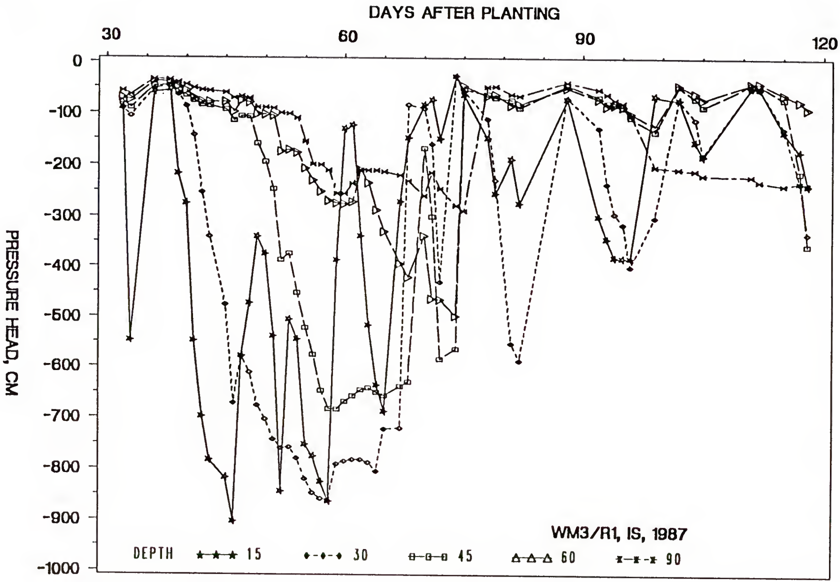


Fig. C-2.- Continued

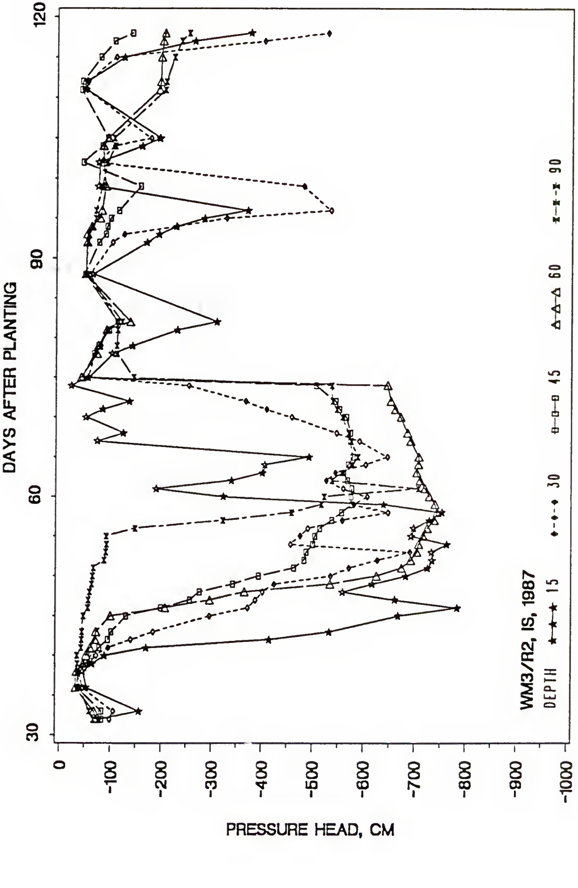


Fig. C-2.- Continued

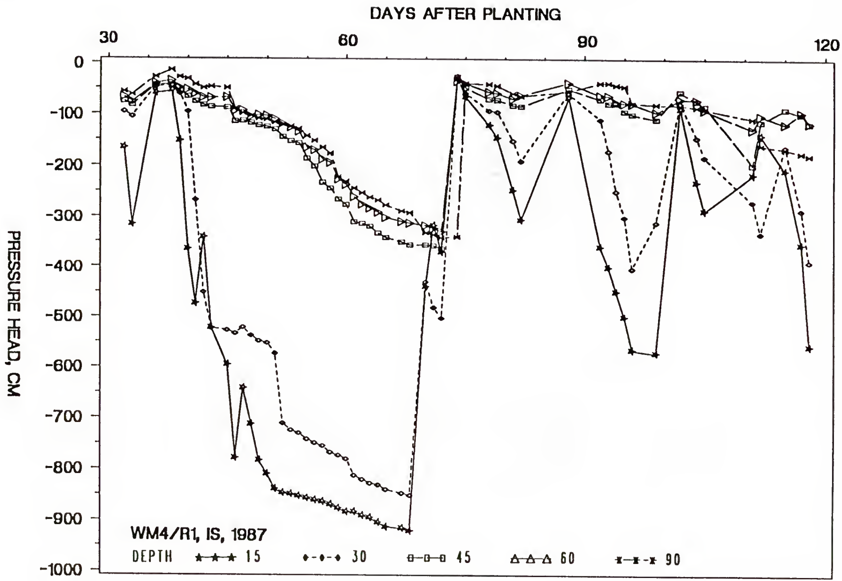


Fig. C-2.- Continued

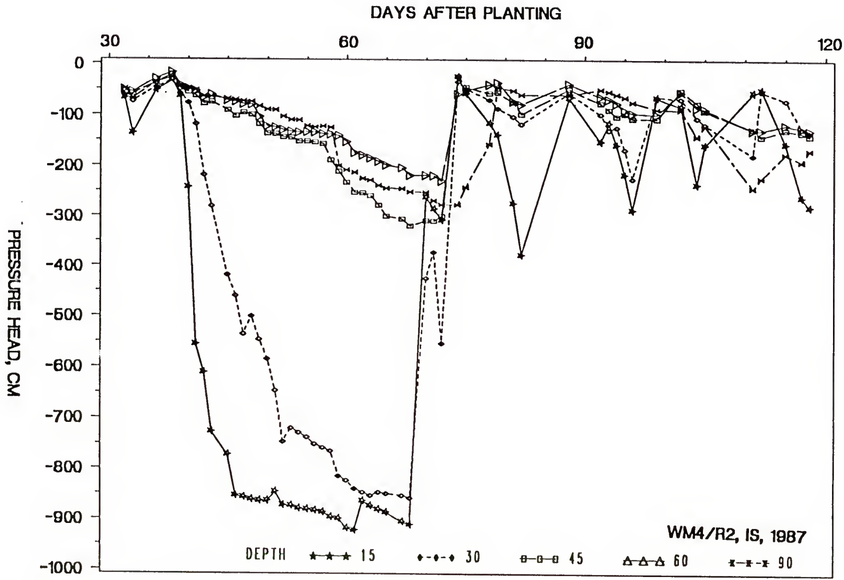


Fig. C-2.- Continued

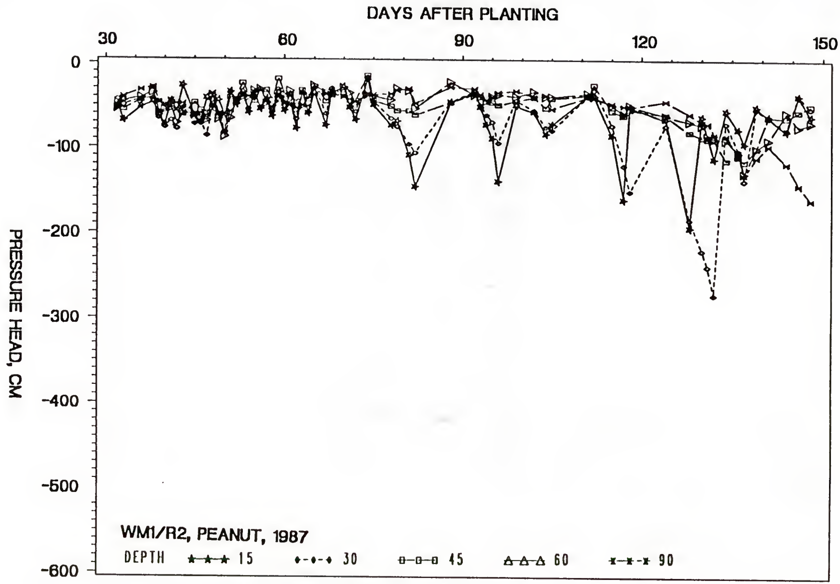


Fig. C-3. Daily pressure heads in the root zone of Southern Runner peanut, Gainesville, 1987.

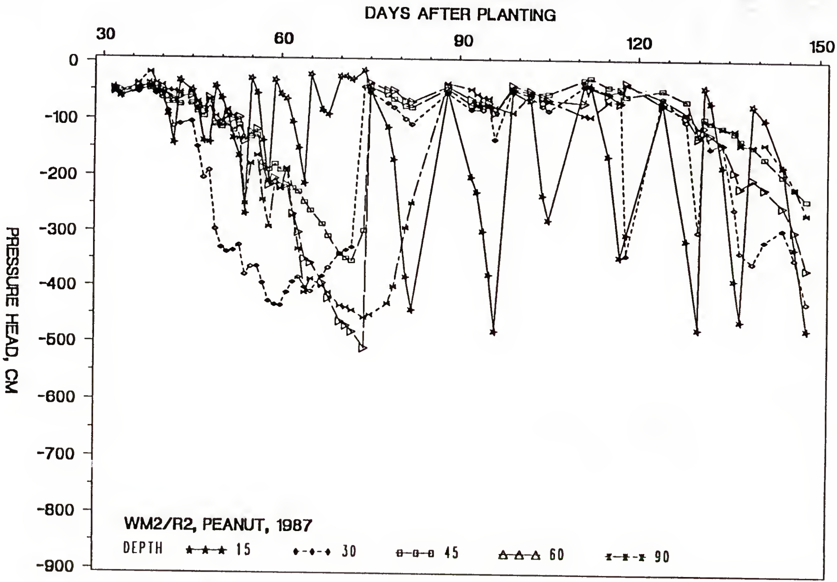


Fig. C-3. Continued

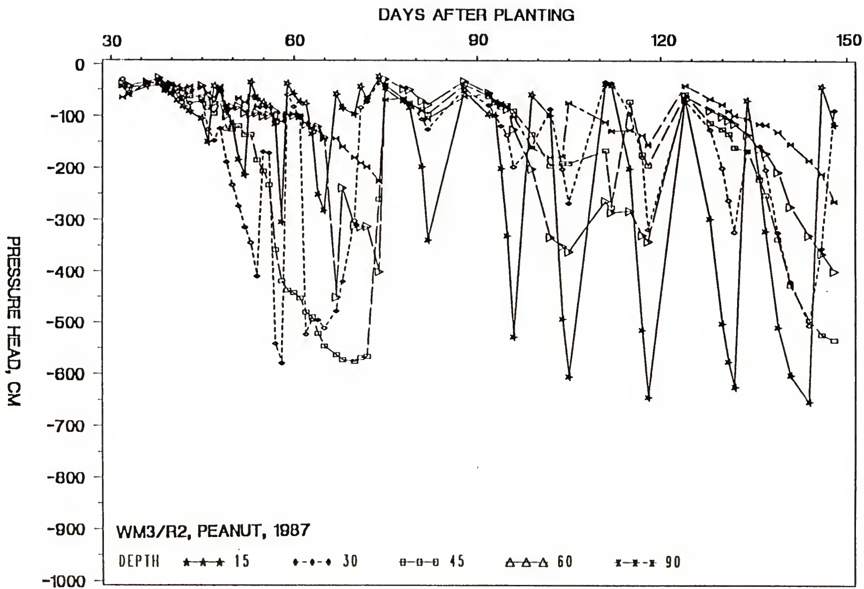


Fig. C-3.- Continued

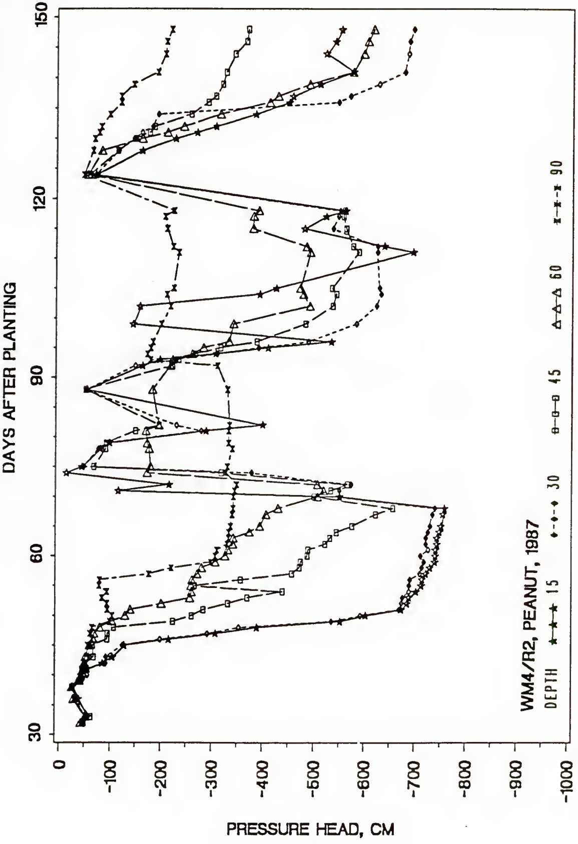


Fig. C-3.- Continued

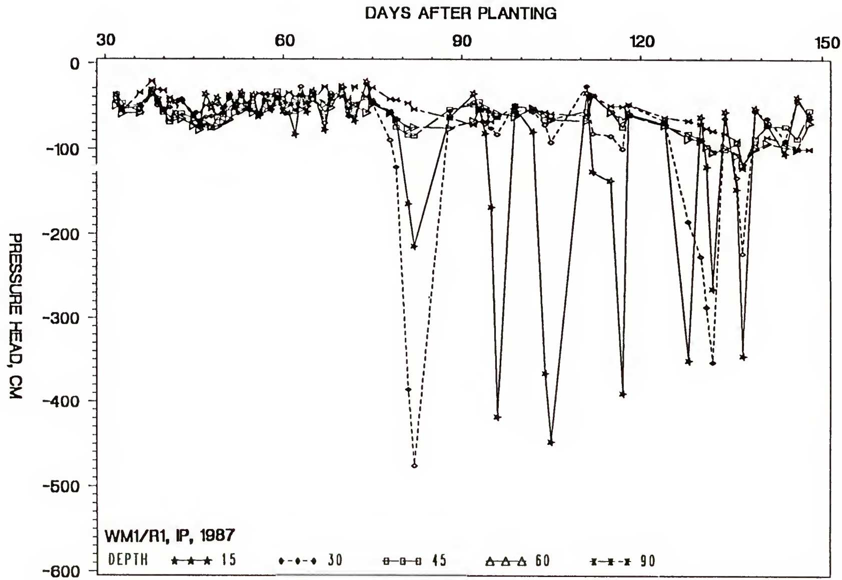


Fig. C-3.- Continued

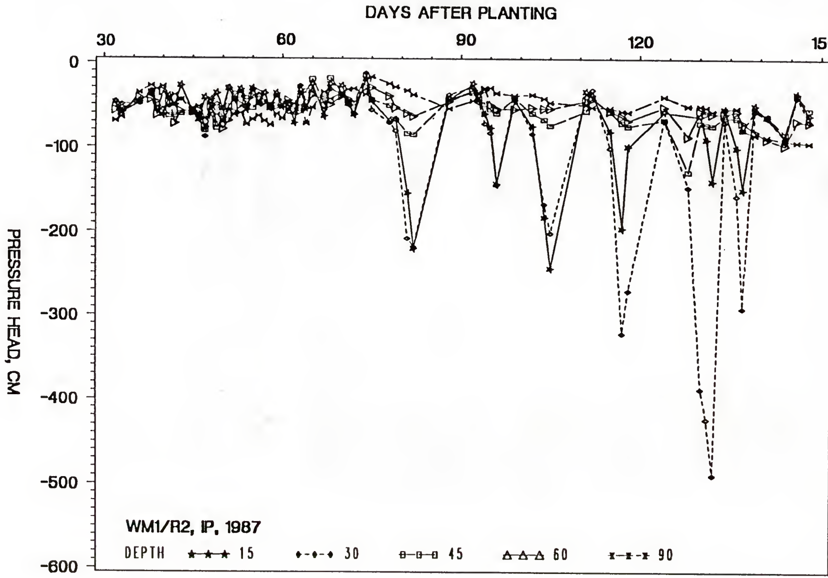
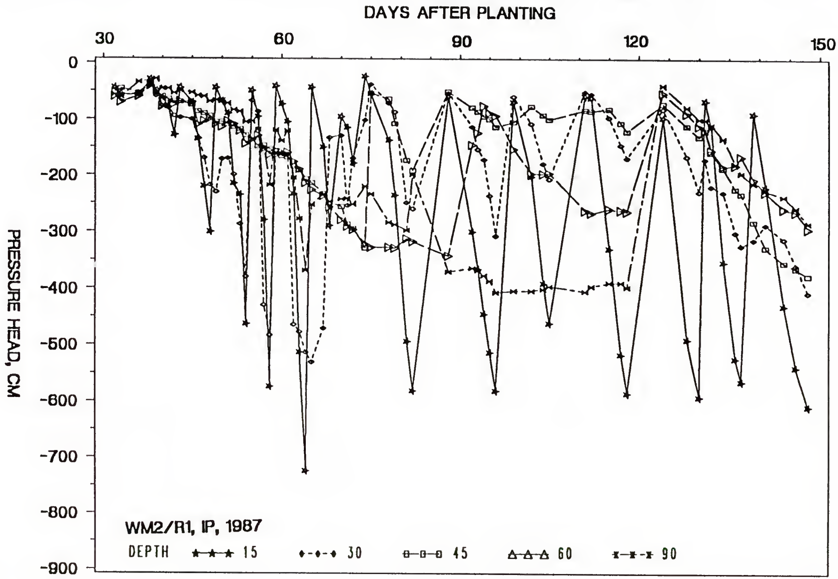


Fig. C-3.- Continued



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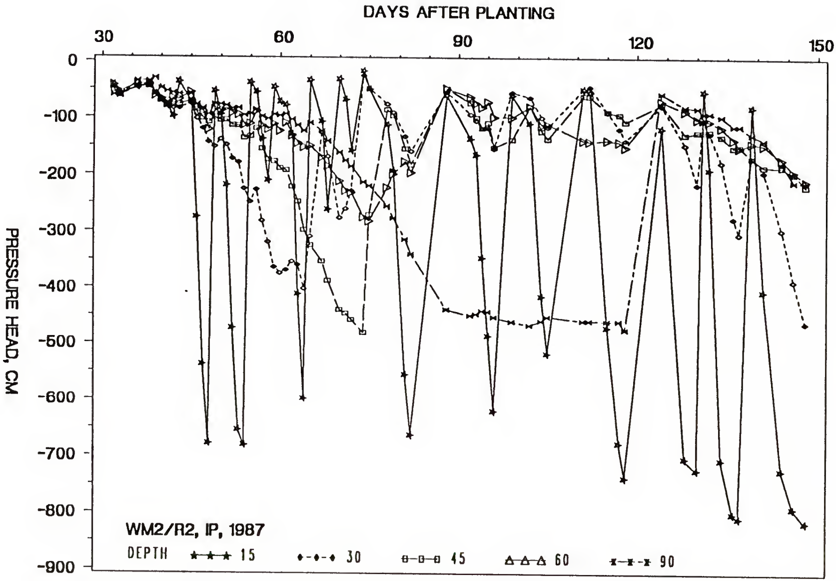

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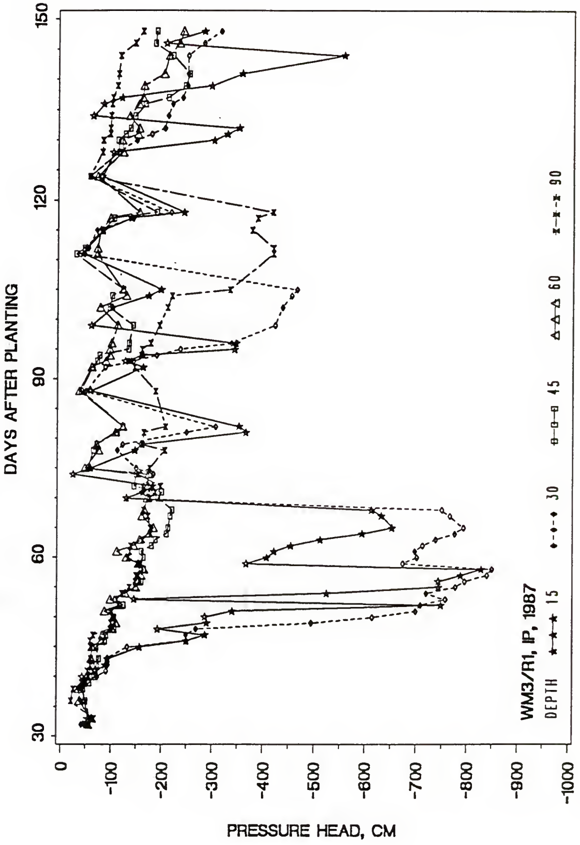

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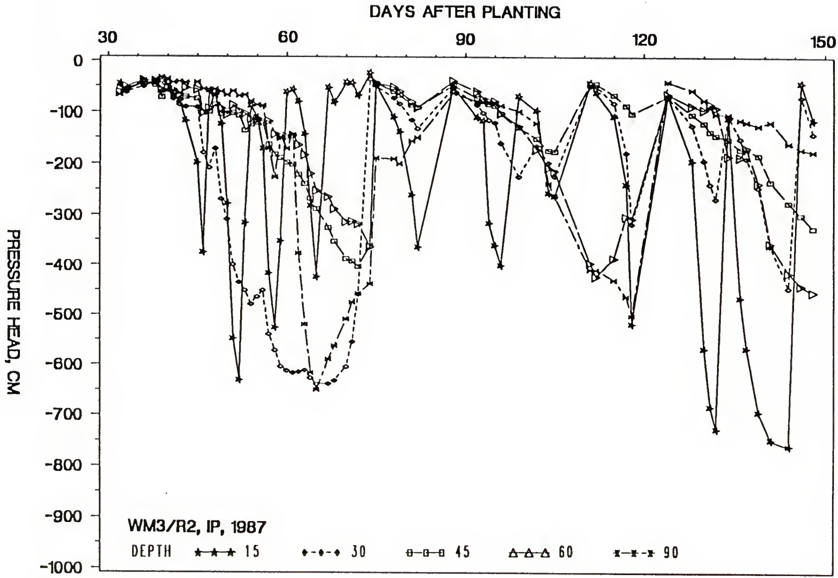

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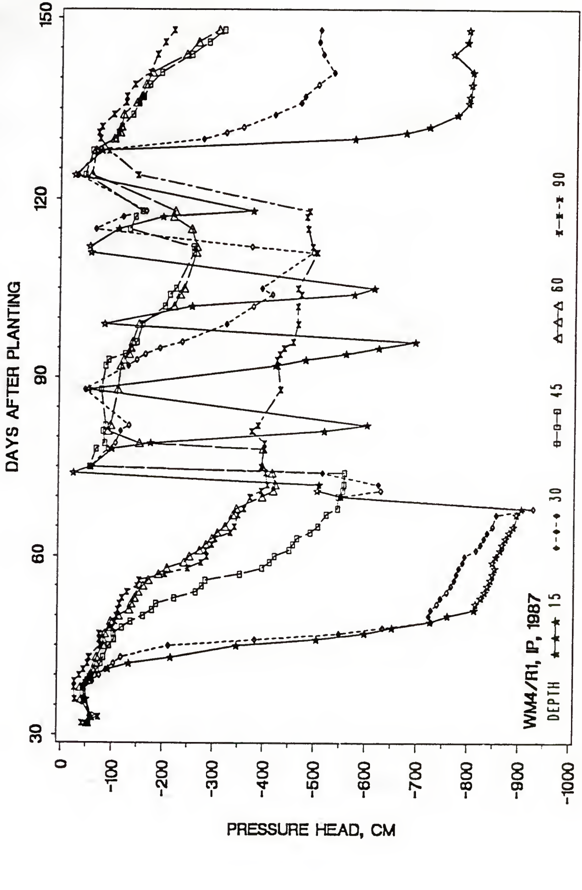

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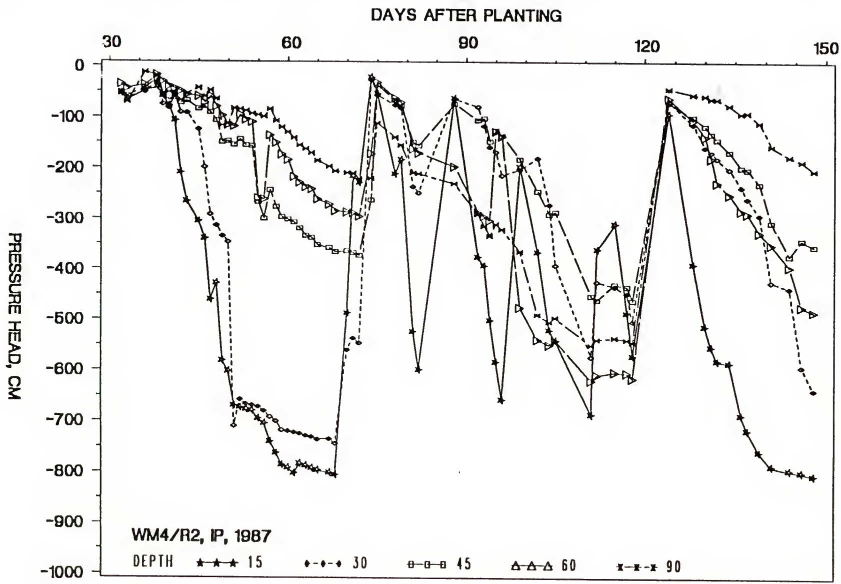

Fig. C-3.- Continued

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BIOGRAPHICAL SKETCH

Michel Omoko was born in Bafia, Cameroon, on November 23, 1950. He received his bachelor's degree in geology at the University of Yaoundé, Cameroon, in 1975. The same year, he was awarded a government scholarship to pursue graduate studies in France. He attended the University of Grenoble (1975-1976) and then the University of Bordeaux (1976-1977), where he received a master's degree in geology (1976) and the Diploma of Advanced Studies in Geohydrology (1977), respectively. He then returned to his home country and worked part-time as Assistant Lecturer at the University of Yaoundé (1977-1978). In 1978 he was hired as Assistant Lecturer at the University Center of Dschang (UCD), Department of Soil Science.

His responsibilities at UCD involved teaching five annual courses in geology, geohydrology and introductory soil physics, coordinating the first-year students and conducting research toward a Doctorate of third cycle with the University of Bordeaux. He completed his degree in February 1984 and was promoted to Lecturer the same year.

In August 1985 he was awarded a scholarship by the Cameroon/USAID Agricultural project to pursue studies leading to a Ph.D. in soil science. He was admitted to the Department of Soil Science at the University of Florida in January 1986, after three months of English training at the English Language Institute.

He is married to Martine Nya, and they have two sons and one daughter attending public school in Gainesville.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

L.C. Hammond, Chairman
Professor of Soil Science

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P.S.C. Rao
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